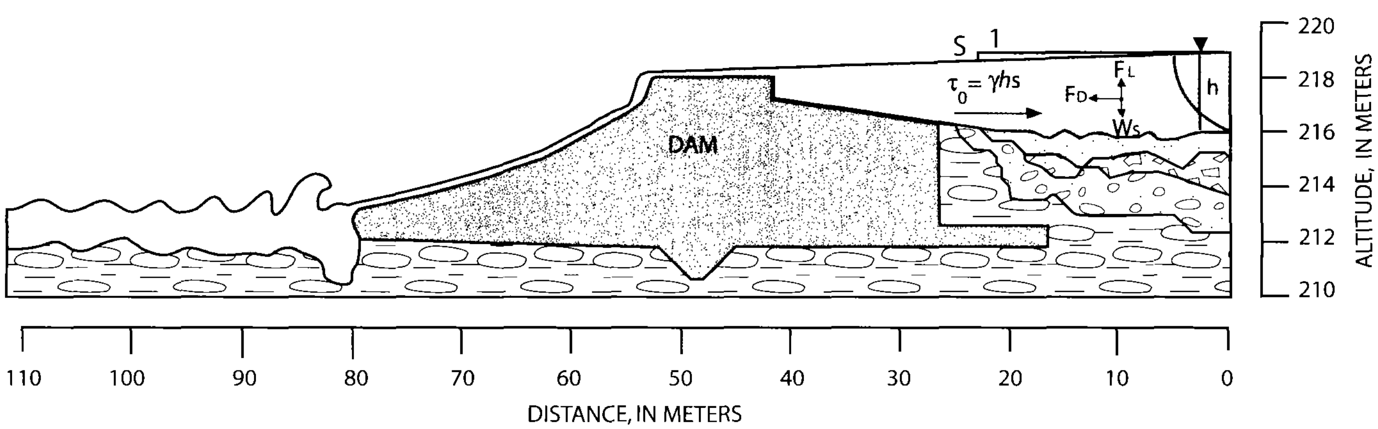
USGS
science for a changing world

In collaboration with the
U.S. Environmental Protection Agency, Region V, and the
Michigan Department of Environmental Quality

A Pre-Dam-Removal Assessment of Sediment Transport for Four Dams on the Kalamazoo River between Plainwell and Allegan, Michigan



Scientific Investigations Report 2004-5178

U.S. Department of the Interior
U.S. Geological Survey

A Pre-Dam-Removal Assessment of Sediment Transport for Four Dams on the Kalamazoo River between Plainwell and Allegan, Michigan

By Atiq U. Syed, James P. Bennett, and Cynthia M. Rachol

In collaboration with the
U.S. Environmental Protection Agency, Region V, and the
Michigan Department of Environmental Quality

Scientific Investigations Report 2004-5178

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

U.S. Geological Survey, Reston, Virginia: 2005
For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

For more information about the USGS and its products:
Telephone: 1-888-ASK-USGS
World Wide Web: http://www.usgs.gov/

Suggested citation:
Syed, A.U., Bennett, J.P., and Rachol, C.M., 2005, A pre-dam-removal assessment of sediment transport for four dams on the Kalamazoo River between Plainwell and Allegan, Michigan: U.S. Geological Survey Scientific Investigations Report 2004-5178, 41 p.

Contents

Figures

Tables

Conversion Factors and Abbreviations

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square meter (m^2)	10.76	square foot (ft^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
megagram per day (Mg/d)	1.102	ton per day (ton/d)
megagram per year (Mg/yr)	1.102	ton per year (ton/yr)
	Density	
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

List of symbols

Q	flow rate in the channel
Z_1 & Z_2	water-surface elevation at the upstream and downstream channel location
A_1 & A_2	cross sectional areas at the upstream and downstream channel location
S_f	frictional slope
S	surface water slope
D	hydraulic depth
T	channel width at the water surface
h	flow depth
n	Manning's roughness coefficient
τ_0	channel bottom shear stress
V	flow velocity
f_i	the ith size fraction of sediment grain
ϕ_i	dimensionless bedload transport
g	acceleration due to gravity with a value of 9.8 m/s^2
bi	unit volumetric bedload transport rate
d_i	particle size for size fraction i

s	ratio of specific gravity of the bed material
τ'_*	dimensionless channel bottom shear stress
$\tau_{*_{cr}}$	critical Shield's stress
γ	unit weight of water
d_{50}	median bed-sediment size
μ	stream velocity at elevation z above the streambed
k	Von Karman's constant with a value of 0.4
z_0	characteristic roughness height and is the distance above the bed at which zero velocity occurs
μ_*	shear velocity
τ	boundary shear stress
ρ	density of fluid
C_z	concentration at elevation z above the bed
v_s	fall velocity of the sediment
a	height above the bed at which the reference concentration is specified
C_a	reference level concentration
C_b	volume concentration of sediment in the bed with specified value of 0.65
γ_o	dimensionless parameter, with a default value of 0.004
S'_*	normalized excess shear stress or transport strength
Δhv	upstream velocity head minus the downstream velocity head
L	distance between two cross sections
K	a coefficient taken to be zero for contracting reaches and 0.5 for expanding reach

A Pre-Dam-Removal Assessment of Sediment Transport for Four Dams on the Kalamazoo River between Plainwell and Allegan, Michigan

By Atiq U. Syed, James P. Bennett, and Cynthia M. Rachol

Abstract

Four dams on the Kalamazoo River between the cities of Plainwell and Allegan, Mich., are in varying states of disrepair. The Michigan Department of Environmental Quality (MDEQ) and U.S. Environmental Protection Agency (USEPA) are considering removing these dams to restore the river channels to pre-dam conditions.

This study was initiated to identify sediment characteristics, monitor sediment transport, and predict sediment resuspension and deposition under varying hydraulic conditions. The mathematical model SEDMOD was used to simulate streamflow and sediment transport using three modeling scenarios: (1) sediment transport simulations for 730 days (Jan. 2001 to Dec. 2002), with existing dam structures, (2) sediment transport simulations based on flows from the 1947 flood at the Kalamazoo River with existing dam structures, and (3) sediment transport simulations based on flows from the 1947 flood at the Kalamazoo River with dams removed. Sediment transport simulations based on the 1947 flood hydrograph provide an estimate of sediment transport rates under maximum flow conditions. These scenarios can be used as an assessment of the sediment load that may erode from the study reach at this flow magnitude during a dam failure.

The model was calibrated using suspended sediment as a calibration parameter and root mean squared error (RMSE) as an objective function. Analyses of the calibrated model show a slight bias in the model results at flows higher than 75 m^3/s; this means that the model-simulated suspended-sediment transport rates are higher than the observed rates; however, the overall calibrated model results show close agreement between simulated and measured values of suspended sediment.

Simulation results show that the Kalamazoo River sediment transport mechanism is in a dynamic equilibrium state. Model results during the 730-day simulations indicate significant sediment erosion from the study reach at flow rates higher than 55 m^3/s. Similarly, significant sediment deposition occurs during low to average flows (monthly mean flows between 25.49 m^3/s and 50.97 m^3/s) after a high-flow event. If the flow continues to stay in the low to average range the system shifts towards equilibrium, resulting in a balancing effect between sediment deposition and erosion rates.

The 1947 flood-flow simulations show approximately 30,000 m^3 more instream sediments erosion for the first 21 days of the dams removed scenario than for the existing-dams scenario, with the same initial conditions for both scenarios. Application of a locally weighted regression smoothing (LOWESS) function to simulation results of the dams removed scenario indicates a steep downtrend with high sediment transport rates during the first 21 days. In comparison, the LOWESS curve for the existing-dams scenario shows a smooth transition of sediment transport rates in response to the change in streamflow. The high erosion rates during the dams-removed scenario are due to the absence of the dams; in contrast, the presence of dams in the existing-dams scenario helps reduce sediment erosion to some extent.

The overall results of 60-day simulations for the 1947 flood show no significant difference in total volume of eroded sediment between the two scenarios, because the dams in the study reach have low heads and no control gates. It is important to note that the existing-dams and dams-removed scenarios simulations are run for only 60 days; therefore, the simulations take into account the changes in sediment erosion and deposition rates only during that time period. Over an extended period, more erosion of instream sediments would be expected to occur if the dams are not properly removed than under the existing conditions. On the basis of model simulations, removal of dams would further lower the head in all the channels. This lowering of head could produce higher flow velocities in the study reach, which ultimately would result in accelerated erosion rates.

Introduction

In the 20th century, more than 76,000 dams were constructed in the United States to provide hydroelectric power, flood protection, improved navigation, and water storage for irrigation and water supply (U.S. Army Corps of Engineers, 1996). These dams and impoundments provided sufficient benefits during their useful life; however, because of limited life expectancy, most of them lost utility through reservoir sedimentation or structural decay. The magnitude of the aging problem is reflected by the estimated 85 percent of the dams in the United States that will be near the end of their operational lives by 2020 (Federal Emergency Management Agency, 1999).

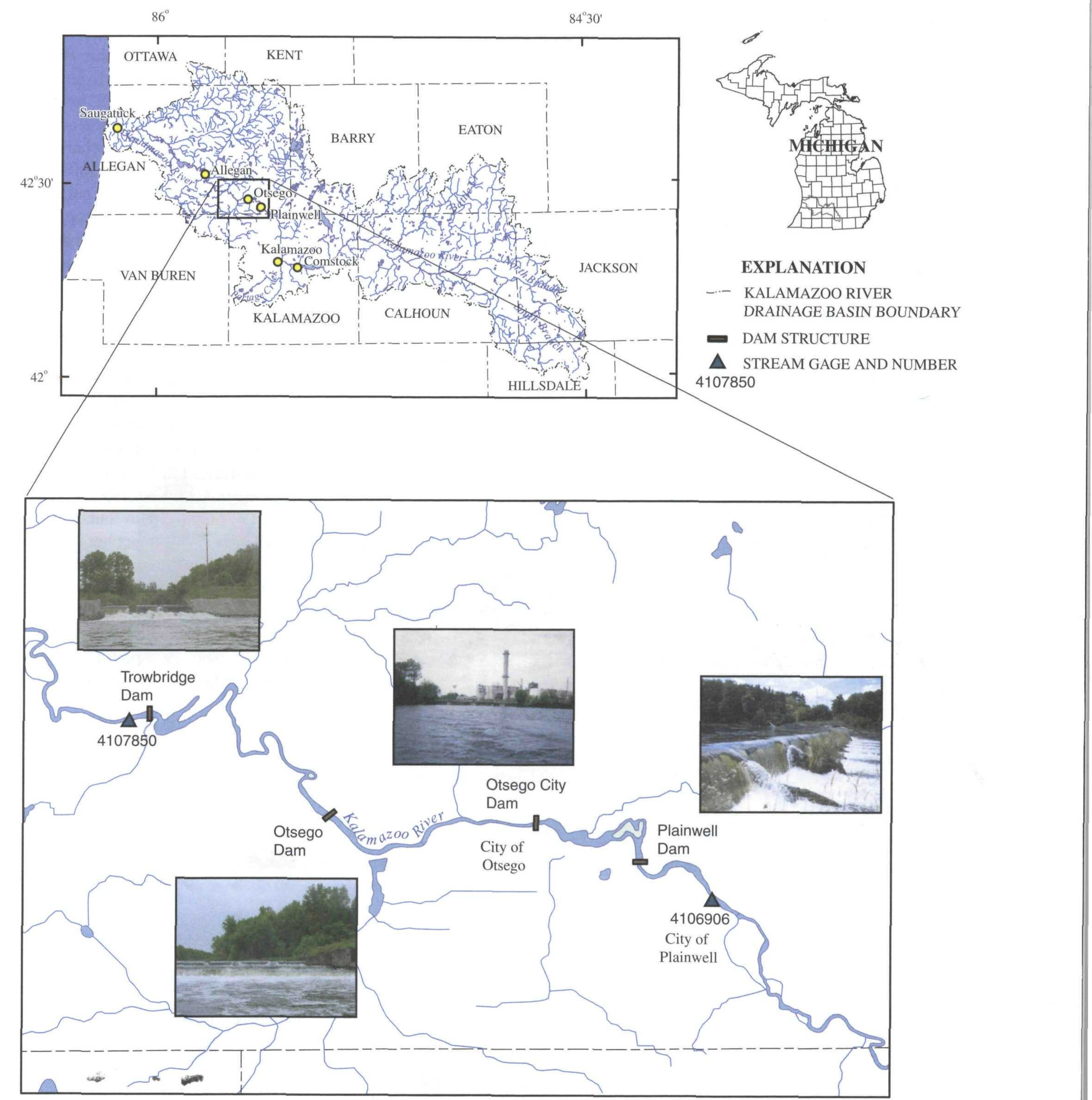
Since the late 1990s, dam removal has become a hotly debated topic, owing to the convergence of economic, environmental, and regulatory concerns (Doyle and others, 2003). Adding to the debate over dam removal is the emerging awareness of contaminated sediments behind these structures. Release of contaminated sediments complicates the issue because it could result in altered water-quality and possible damage to threatened and endangered species. Such a problem of aging dams has developed on the Kalamazoo River between Plainwell and Allegan, Mich. (fig. 1). All four dams in this river reach are in varying states of disrepair and are under consideration by the Michigan Department of Environmental Quality (MDEQ) and U.S. Environmental Protection Agency (USEPA) for future removal to restore the river channels to pre-dam conditions. Sediments associated with these impoundments are contaminated with polychlorinated biphenyls (PCB) (Blasland, Bouck & Lee, Inc., 1994). Therefore, removal of these dams, either by catastrophic flood or engineered deconstruction, would mobilize the contaminated sediments and potentially damage the natural aquatic habitat downstream. Previous engineering studies and construction efforts have addressed stabilization of some of these dams, but the effects of dam removal on sediment transport are basically unknown. This study was done by the U.S. Geological Survey (USGS) in cooperation with the USEPA and MDEQ to identify sediment characteristics, monitor sediment transport, and predict sediment resuspension and deposition under varying hydraulic conditions. Sediment characteristics and distribution are described in detail in a two-report series that were produced during the first phase of this project (Rheaume and others, 2000). The current study identifies sediment loads and transport rates in the study reach.

Purpose and Scope

The purpose of this report is to describe sediment transport under varying hydraulic conditions in the alluvial section of the Kalamazoo River between Plainwell and Allegan, Mich. A mathematical sediment transport model, SEDMOD, was used to simulate streamflow and sediment transport. Three modeling scenarios were generated to assess sediment transport under varying hydraulic conditions: (1) sediment transport simulations for 730 days (Jan. 2001 to Dec. 2002), with existing dam structures, (2) sediment transport simulations based on flows from the 1947 flood at the Kalamazoo River with existing dam structures, and (3) sediment transport simulations based on flows from the 1947 flood at the Kalamazoo River with dams removed. Sediment transport simulations based on the 1947 flood hydrograph provide an assessment of the sediment load that may erode from the study reach at this flow magnitude during a dam failure.

Model implementation and calibration efforts discussed in the report focused on producing a sediment transport model that estimates the total volume of sediments in the backwater section of each dam and the time evolution of total sediment transport rates in the study area. The model was calibrated using root mean squared error (RMSE) as an objective function for measuring the goodness-of-fit between model-simulated suspended-sediment transport rates and observed suspended-sediment data.

The Kalamazoo River network, especially the braided section between the Plainwell Dam and Otsego City Dam is a complex hydraulic system. The direction of flow in some of the braided channels is streamflow dependent, meaning reverse flow can occur at certain flow rates. Although SEDMOD is capable of computing flow and sediment transport through multiple openings/networks, it cannot take into account reverse flow. Therefore, only those braided channels between the Plainwell and Otsego City Dam of the study reach have been modeled where the streamflow is in a single direction and channel-bottom elevations are sloped enough that reverse flow does not occur.



Sources:
City names and locations from U.S. Geological Survey digital raster graphics.
Hydrologic divides from Michigan Deparment of Environmental Quality Land and Water Management.
Hydrologic features and county boundaries from Michigan Resource Information System

0 1 2 MILES
0 1 2 KILOMETERS

Figure 1. Kalamazoo River study reach and location of four dams.

Previous Studies

Several water-quality and hydraulic-modeling studies were done previously on the Kalamazoo River to address PCB issues as well as water-quality impairments from conventional contaminants. The most extensive previous modeling investigation related to PCB in the Kalamazoo River is described in the "Kalamazoo River Remedial Action Plan Second Draft" prepared for the Michigan Department of Natural Resources (MDNR) (Blasland, Bouck & Lee, Inc., 1994). This document presents a steady-state PCB mass-balance model developed by Nuclear Utility Services Corporation (NUS). This model was developed to assess the relative effectiveness of remedial actions. The model was based on a limited dataset and could not be used to forecast PCB time trends (Blasland, Bouck & Lee, Inc., 1994).

Another PCB fate model was developed by Limno-Tech Incorporated (LTI). Development, calibration, and model application are documented in "Modeling Analysis of PCB and Sediment Transport in Support of Kalamazoo River Remedial Investigation/Feasibility Study" (Quantative Environmental Analysis, 2001). The LTI PCB fate model is a one-dimensional model and consists of four submodels: (1) HEC-6 hydraulics model, (2) bank erosion, (3) KALSIM sediment transport, and (4) KALSIM PCB fate and transport.

A review of the LTI model by Quantitative Environmental Analysis (QEA) for the MDEQ included analysis of the LTI report and evaluation and testing of various submodels (for example, HEC-6, KALSIM, and bank erosion models). The QEA report indicates that LTI models cannot be used as a management tool at present (Quantative Environmental Analysis, 2001).

Description of the Study Reach

The study area consists of approximately a 19-km reach of the Kalamazoo River, starting 2,276 m upstream from the Plainwell Dam, and ending approximately 600 m downstream from the Trowbridge Dam (fig. 2). This section of the Kalamazoo River has meandering channels and point bars, and it flows through a broad, well-defined flood plain. In 2000, two streamgages were installed to monitor flow rates and collect data such as water temperature and specific conductance. The Plainwell gage (04106906) was installed approximately 1.6-km upstream from the Plainwell Dam and the Allegan gage (04107850) was installed approximately 300 m downstream from the Trowbridge Dam (fig. 1). The Plainwell gage has a drainage area of 3,263 km^2 and the Allegan gage has a drainage area of 3,963 km^2 (Blumer and others, 2003).

The study reach has four low-head dams (fig. 1). Three of the dams, Plainwell, Otsego, and Trowbridge, were decommissioned as power generators in the mid-1960s (Rheaume and others, 2000). The superstructures consisting of powerhouses, gates, upper abutment walls, and some of the spillways were removed in 1985–86 (Camp Dresser & McKee, 1999a). The current (2004) structures consist of only the dam foundations. The Otsego City Dam superstructure is still intact but the dam is not functional. For modeling purposes, the entire study reach was divided into 15 channels, with a total of 131 transects (fig. 2). Channels 1 to 11 are between the Plainwell and Otsego City Dams; channels 12 to 14 are between the Otsego City, Otsego, and Trowbridge Dams. Channel 15, which is a short reach composed of 5 transects, is below the Trowbridge Dam (fig. 2).

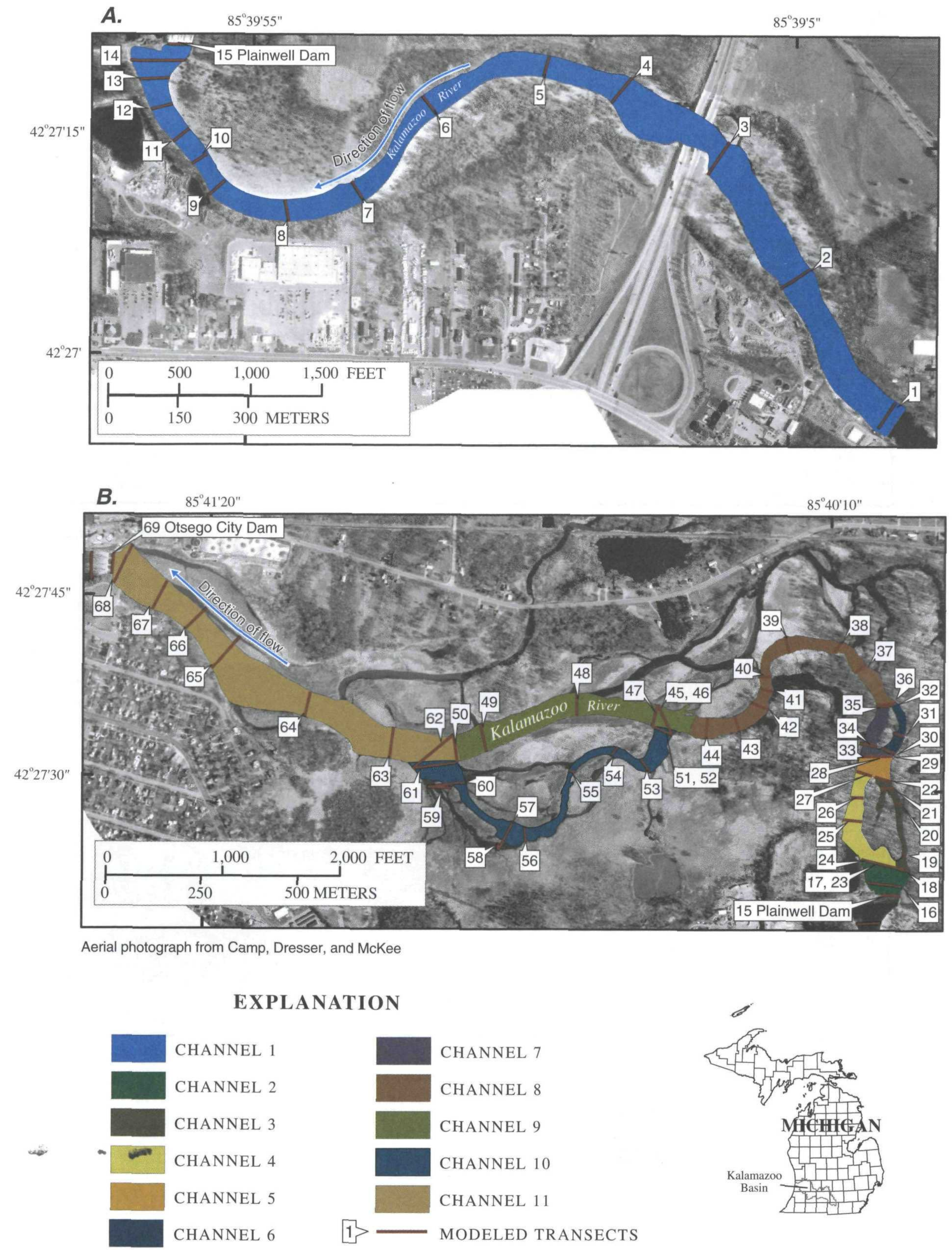


Figure 2. Modeled river channel and transect locations at the *A*, Plainwell; *B*, Otsego City; *C*, Otsego; and *D*, Trowbridge Dams.

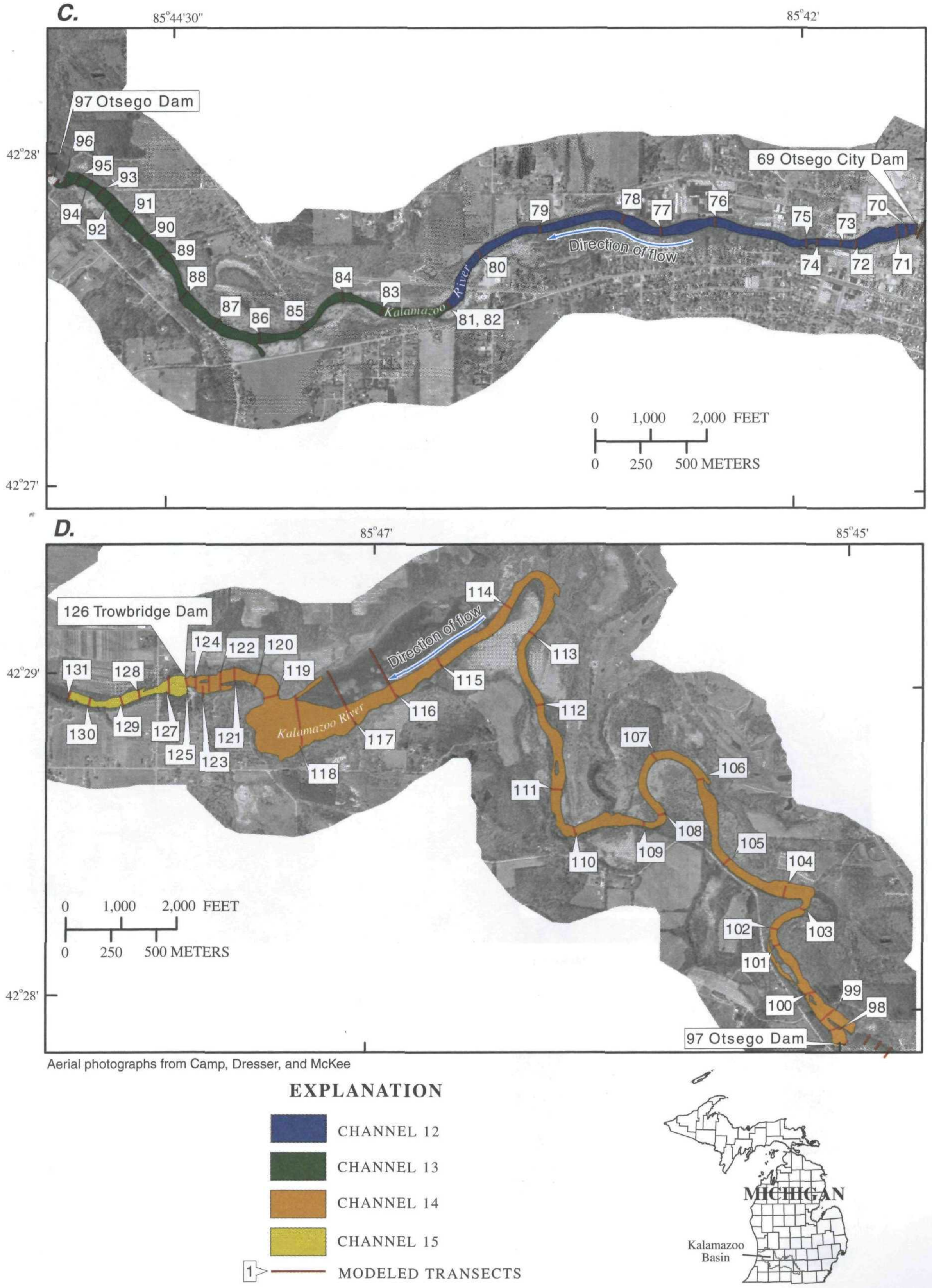


Figure 2—Continued. Modeled river channel and transect locations at the *A*, Plainwell; *B*, Otsego City; *C*, Otsego; and *D*, Trowbridge Dams.

Field Data Collection Methods

Field data included bed-sediment cores, transect surveys, and suspended and bedload sample collection. A brief summary of the field data collection methods is presented in the next two sections.

Transect Surveying and Sediment Coring

Data for approximately 160 river transects were collected between the Plainwell and Allegan streamgages. The transect spacing was based on the average river width at each dam in the study reach. For example, transect 1 in each impoundment was laid out as close to the dam as safety would allow. Transects 2, 3, and 4 were spaced at intervals of one river width. Transects 5, 6, and 7 were spaced at intervals of two river widths. Transects 8 and higher were spaced at four river widths until the backwater end of each impoundment was reached. Increased river velocities, riffles, and debris islands typically indicated the backwater edge.

Reference points (RP) were established at each transect by driving a steel fencepost into the bank, close to edge of water. Elevations of the RPs were surveyed to 0.03048 m by Camp Dresser & McKee in fall 2000 (Rheaume and others, 2000). Elevations of bank height and water surface were calculated from the RPs at each transect.

A steel-cable tagline, painted at 1.524 m intervals, was stretched perpendicular to the river at each transect. Global Positioning System (GPS) coordinates were noted at both attachment points. The river width was divided into an average of 10 equal sections for the measurement of water depth, water velocity, and sediment thickness. A GPS coordinate was noted at each section. Water depth and velocity data were obtained by standard USGS methods using a boat-cable measuring device equipped with an A-reel, 6.8-kg or 13.6-kg weight, and a Price AA standard current meter (Rheaume and others, 2000).

Auger-point samples and sediment cores were collected along each transect in the impoundments. Miscellaneous auger samples were collected between transects to improve contouring accuracy. Thickness of sediment was obtained by boring with a 0.305 m long by 38 mm diameter auger bit with 1.2 m extension pipes. The depth of the fill that overlaid the original river alluvium was identified when the auger reached resistance and a grinding sound on cobble and stones could be heard. Sediment core samples were collected by driving a 3-m length of 32-mm diameter PVC pipe into the river bottom until it reached resistance. Changes in texture and color were described and recorded in the field. Lithologic descriptions of the cores are summarized in Rheaume and others (2000). A total of 82 representative samples of these cores were collected and sieved with U.S. Standard Sieves ranging from 0.0625 to 16 mm.

Suspended- and Bed-Sediment Data Collection

The suspended-sediment discharge was determined from suspended-sediment concentrations of water samples that were collected in accordance with the procedures described in Edwards and Glysson (1999). Bedload samples were collected with US BL-84 bedload Sampler, developed by the U.S. Army Corps of Engineers, Waterways Experiment Station (http://fisp.wes.army.mil). These samples were collected near the Plainwell gage and downstream from the Trowbridge Dam, near the Allegan gage. Data from the bedload and suspended-load samples collected at the Plainwell gage were used as the input sediment supply rate in the model simulations. Suspended sediment data collected near the Allegan gage were used to calibrate the model. The bedload and suspended-load data are presented in the appendix section of this report.

Description of the Sediment-Transport Model

For this study, the mathematical sediment transport model SEDMOD was used (Bennett, 2001). SEDMOD is a steady-state, one-dimensional model that simulates streamflow and sediment transport in a single channel or networks of channels and computes the resultant scour and fill at any given location in the channel reach. The model treats input hydrographs as stepwise steady state, and the flow-computation algorithm switches between subcritical and supercritical flow, dictated by channel geometry and flow rate. Because changes in channel geometry due to erosion and deposition occur relatively slowly as compared to the timeframe of a flow hydrograph, the model approximates the hydrograph using a sequence of steady flows. The model allows the user to specify 20 sediment sizes and any number of layers of known thickness. A brief description of the model structure and computational algorithms is given below.

Flow Simulations

The model accepts time-varying hydrographs but provides a steady-state solution for each instantaneous streamflow corresponding to a particular instant in time. The transport-related parameters are computed from the resulting hydraulic variables for that particular time increment. The water-surface elevation profile is computed by means of Newton iteration in the following form (Chaudhry, 1993):

$$f(Z_1) = Z_1 + \frac{Q^2}{2g}(A_1^{-2} - A_2^{-2}) - \Delta x \cdot S_f - Z_2 = 0, \qquad (1)$$

where $Q = v * A$ is the flow rate in the channel, and subscripts 1 and 2 refer respectively to the upstream and downstream sections; Z_1 & Z_2 is the water-surface elevation at locations 1 and 2 (fig. 3); A_1 & A_2 are the cross sectional areas at locations 1 and 2; and S_f is the frictional slope.

For steady uniform flow, the frictional slope (S_f) and surface slope (S) are equivalent; therefore, the model uses Manning's formulation to solve (S_f):

$$v = \frac{1}{n}D^{2/3}S^{1/2}. \qquad (2)$$

In equation 2, the hydraulic depth, D equals A/T where D is the depth, A is the channel cross sectional area, and T is the channel width at the water surface. For a wide channel, D and the flow depth, h (shown in fig. 3) are equivalent. Thus, the frictional slope is obtained from the following equation:

$$S_f = Q^2 \cdot n_1 \cdot n_2 \cdot \sqrt{\frac{(T_1 \cdot T_2)^2}{(A_1 \cdot A_2)^8}}. \qquad (3)$$

In the above equation, n is the Manning's roughness coefficient, and T is channel top width and the subscripts refer to the upstream location 1 and downstream location 2.

In figure 3, the upstream and downstream locations are shown as 1 and 2, with h as the depth of flow and z as the reference bottom elevation. The other variables in figure 3 include bottom shear stress (τ_o), velocity (v), and surface slope (S).

The upstream boundary condition in the model is always a specified discharge, with five user-specified boundary conditions for the downstream channel section. These include specified water-surface-elevation time series, hydraulic depth versus streamflow rating curve, normal flow depth for the downstream channel with specified slope, water-surface elevation at a specified internal channel junction, or a sharp-crested weir elevation and crest width.

The model allows network simulations, which may consist of several channels interconnected at junctions. The channel junctions are assumed to have no plan area, so no storage of water or sediment is recorded into it; also, all channels entering or leaving the junctions have the same water-surface elevation. For each time step, the flow-simulation algorithm iterates through the entire network until neither the downstream water-surface elevation nor the input discharge varies significantly for any channel (Bennett, 2001). Water-surface elevation at ajunction is determined by adjusting the sum of the streamflow leaving the junction to that entering by less than a factor of 1 in 1,000. After all the flow rates have been determined in all the channels, sediment is distributed in the modeled system in proportion to the flow rates.

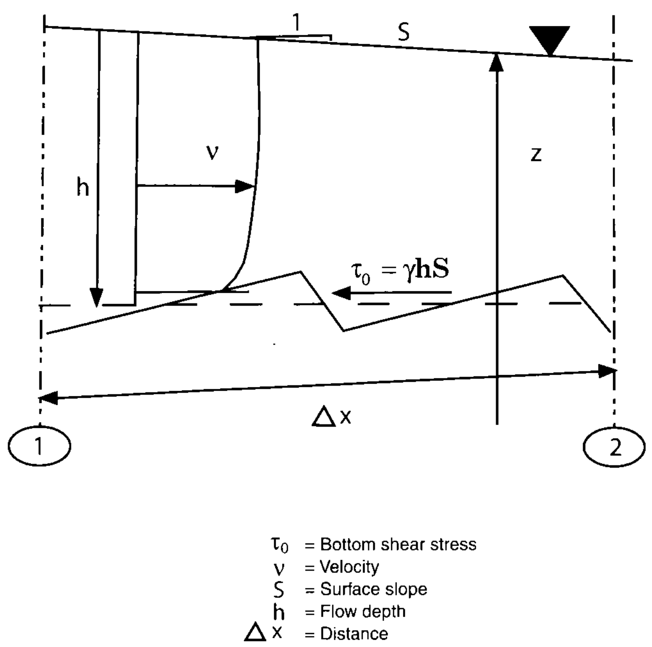


Figure 3. Definition of flow-related variables (from Bennett, 2001).

Bedload Transport

The bedload-transport equations for this model follow the work of Wiberg (1987) in incorporating Meyer-Peter-type formulation. The Wiberg model is based on the equations of motion for a sediment grain near a noncohesive bed, which include drag, lift, gravity, and relative concentration. A numerical solution of these equations will specify a path for the saltating particles, from which saltation height, length, and particle velocity can be computed. The model can be used to determine the thickness of the saltation layer and the amount of material transported therein (Bennett, 2001).

Wiberg (1987) concludes that a Meyer-Peter-type formulation works best to compute the bedload transport, assuming transport in equilibrium with bed sediment of known size distribution f_i for the i th size fraction, which is shown in the equation below:

$$\phi_i = f_i\phi_0(\tau'_* - (\tau_*)_{cr})^{1.5}. \qquad (4)$$

In equation 4, the dimensionless bedload transport is:

$$\phi = bi/[(s-1)gd_i^3]^{0.5}, \qquad (5)$$

where bi is the unit volumetric bedload transport rate and d_i is the particle size for size fraction i, and s is the ratio of specific gravity of the bed material. Also in equation 4, the dimensionless bottom shear stress is:

$$\tau'_* = \frac{\tau_o}{\gamma(s-1)d_i} \qquad (6)$$

where γ is the unit weight of water and τ_o is the channel-bottom shear stress (fig. 3) corrected for the form drag of any bed forms that are present. The critical shield stress, $\tau_{*_{cr}}$, is based on d_{50}, the median bed-sediment size (50 percent of the bed particles are finer); that is, $\tau_{*_{cr}}$ results from equation 6, with d_i replaced by d_{50} and τ'_0 by $\tau_{*_{cr}}$, the shear stress for incipient motion for particles of the median bed-sediment size. The model uses a value of $\phi_o = 8$, as adapted by Meyer-Peter and Muller (Bennett, 2001). This is a default value in the model and is user adjustable.

Suspended-Sediment Transport

Computation of suspended load requires accurate representation of vertical variation of velocity and eddy diffusivity. Shape of the vertical profile of the longitudinal velocity and resistance to flow are determined from the size, shape, and spatial distribution of roughness elements on the channel bed. The velocity profile for fully developed turbulent flow over a plane bed can be expressed as follows (Bennett, 1995):

$$\frac{\mu}{\mu_*} = \frac{1}{k}\ln\left(\frac{z}{z_o}\right). \qquad (7)$$

in which μ is stream velocity at elevation z above the streambed, k is Von Karman's constant with a value of 0.4, z_o is the characteristic roughness height and is the distance above the bed at which zero velocity occurs, and μ_* is shear velocity. The eddy diffusivity for the velocity profile can be determined from the definition of eddy viscosity and Reynolds analogy. Using the definition of eddy diffusivity and differentiating equation 7, one can obtain the eddy diffusivity for a logarithmic velocity profile by use of the following equation (Bennett, 1995):

$$\varepsilon_s = \frac{\tau/\rho}{du/dz} = \kappa\mu_* z(h-z)/h. \qquad (8)$$

In equation 8, τ is the boundary shear stress, and ρ is the density of fluid. Assuming steady, uniform flow and equilibrium transport in the longitudinal direction, the vertical conservation of mass equation for suspended sediment for each size fraction can be solved analytically to yield

$$C_z = C_a\left(\frac{h-z}{z}\frac{1}{h-a}\right)^{\frac{v_s}{\kappa\mu_*}}, \qquad (9)$$

where C_z is the concentration at elevation z above the bed, v_s is the fall velocity of the sediment, and a is the height above the bed at which the reference concentration is specified. Equation 9 is known as the Rouse equation and $\frac{v_s}{\mu_*}$ as the Rouse number. For computing reference-level concentration, the model uses the formulation from Smith and McLean (Bennett, 2001):

$$C_a = \frac{C_b\gamma_o S'_*}{1+\gamma_o S'_*}, \qquad (10)$$

where C_b is the volume concentration of sediment in the bed and is on the order of 0.65, γ_o is a dimensionless parameter, with a default value of 0.004 and is user adjustable during simulations, and S'_* is the normalized excess shear stress or transport strength. This type of formulation in the model is based on the assumption that equilibrium exists between the bed material makeup and the transport above it for a uniform reach.

Model Input Data Structure

The network-structure, channel-geometry, and boundary-condition data of the model reside in two flat files. The first, the network-description file, describes the network interconnections, channel geometry, and sediment sizes and distribution. The second, the boundary condition file, sets the type and timespan of simulation and describes all internal and external boundary conditions.

Network-Description File

In general, the network consists of a numbered sequence of channels for reference by the model algorithms; for example, a total of 15 channels or reaches were in the study reach. The individual channels consist of a minimum of 2 and a maximum of 29 transects. Of the 160 surveyed transects, 125 were used in the model simulation, along with 6 synthesized transects. The 35 transects not included in the model are in the low-flow river reaches between the Plainwell and Otsego City Dams. In these reaches, the streamflow direction is streamflow-stage-dependent, and would require transient flow simulation, which is beyond the scope of this study. The synthesized transects were generated by interpolation between surveyed channel cross sections. These were mainly used at the channel junctions to provide additional data to the model. Therefore, a total of 131 cross sections with 11 junctions were modeled in the entire study reach, cross section 1 being the most upstream transect and cross section 131 the most downstream transect. The sediment-transport algorithm routes sediment in the sequence order in which channel descriptions are supplied.

The hydraulic component of SEDMOD is based on a stage-streamflow boundary condition. The upstream boundary condition is the daily mean flow at the most upstream river transect, and the downstream boundary condition is the daily mean stage at the most downstream transect. The model uses a step-backwater approach to solve for the hydraulic variables in each reach. For each interior channel, streamflow is a variable to be solved for, and the boundary conditions at its ends are water-surface elevations at the respective junctions.

For the 730-day simulation (2001–02 calendar year), daily mean streamflows from the Plainwell gage (04106906) were used as the upstream boundary condition, and stage data from Allegan streamgage (04107850) were used as the downstream boundary condition. For the 1947 flood scenario, daily mean streamflows from streamgaging stations at Comstock (04106000) and Fennville (04108500) were used with necessary adjustments for drainage-basin area. These streamgages were chosen because of an extended flow-data record. The Comstock streamgage is upstream from the Plainwell streamgage, and the Fennville streamgage is downstream from Allegan streamgage.

The model provides a plan-view plot of the simulation area. Therefore, the distance between transects is calculated using its coordinates to locate each transectís base line in the x-y plan view. A Universal Transverse Mercator (UTM) coordinate system was used in the model. Other necessary information for each transect description includes an elevation adjustment factor (which may equal 0), a bedrock elevation or lower scour limit, and Manning's n (based on site material) for the bedrock surface. The scour-limit elevations were based on the elevation at which the sediment core reached resistance and a grinding sound on cobble and stones could be heard. A Manning's n of 0.04 was used for the bedrock material (Sturm, 2001). The Manning's n applicable to the full width of alluvial surface was computed for the individual transect, on the basis of field data. (See the subsequent section on computations of Manning's n). The bank and (horizontal) bedrock segments constitute a no-erosion boundary for each transect. A Manning's n of 0.05 was used for the right and left overbanks (Sturm, 2001), where information regarding vegetation cover and bank elevations could be derived from aerial photos.

Following description of the transect geometry, the characteristics of different layers of sediment were entered into the network-description file. Most of the transects in individual reaches had more than one sediment layer. The layers are numbered from the upper layer downward; and, for each subsequent layer the first record of the layer description includes a layer-surface elevation following the size-distribution code. Sediment size distributions were input into the model as "fraction finer" and the corresponding particle sizes; that is, listing f_i as the volume percentage of the sediment layer that has sizes finer than the particle size d_i thus, d_{50} is the particle size such that 50 percent of the layer-volume consists of finer particles. A total of eight sediment sizes between 0.0625 and 16 mm were used for each individual sediment layer in the model simulations. The final section of the network-description file describes the channel junctions from upstream to downstream.

Boundary-Condition File

The boundary-condition file contains information to set the initial conditions for the model run, determine the temporal extent of the simulation, and specify appropriate boundary conditions for each time step during execution. In general, this file contains all the necessary information applied to the various boundary conditions, such as the upstream flow, the downstream stages, temperature in degree Celsius, and sediment supply rates. The temperature data are necessary to determine fall velocities and critical shear stresses for the particles of the simulated size classes. Water-temperature data were collected at the Allegan streamgage and were used for the entire study section.

One of the data requirements for the model was to specify the total sediment transport rate coming into the study reach at the most upstream channel reach. Because the suspended-sediment field data are reported as a concentration (milligram per liter) and the bedload data are reported as a loading rate (mass per unit time), proper conversion procedures had to be followed to convert them into a transport rate (cubic meter per second). After conversion, the bedload and suspended-load values had to be added to obtain the total transport rate for use by the model.

The final downstream boundary condition specifies the existence of a sharp-crested weir and requires the user to provide an absolute crest elevation and crest length, both in meters. This boundary condition was applied at an internal junction, making it possible to include a low-head dam or diversion structure in the simulation. This boundary condition was applied to all four dams in the study reach. The Plainwell Dam width and depth information were obtained from a study done by Camp Dresser & McKee (1999a). The Otsego City, Otsego, and Trowbridge Dam geometry data were obtained from field study done by the USGS.

Computation of Manning's Roughness Coefficient

The average value of Manning's roughness coefficient for each transect was computed by use of equation 11 (Barnes, 1967). This equation is applicable to a multisection reach of M transects that are designated 1, 2, 3, ...M-1, M. Therefore, the entire Kalamazoo study reach was divided into several channel segments, each composed of a minimum of two and maximum of four transects. Input data into equation 11, such as streamflows and water-surface elevations, were used based on the streamgage records and surveyed channel geometry. The hydraulic radius, cross-sectional area, and wetted perimeter for each transect were computed from the field data using AutoCAD (Autodesk, Inc., 2003). After compiling all the input data, the final computations for Manning's n were done with MathCAD (Mathsoft Engineering and Education, Inc., 2001).

$$n = \frac{1.486}{Q}\sqrt{\frac{(h+hv)_1-(h+hv)_m-[(K\Delta hv)_{1.2}+(K\Delta hv)_{2.3}+\ldots+(K\Delta hv)_{(M-1)M}]}{\frac{L_{1.2}}{Y_1Y_2}+\frac{L_{2.3}}{Y_3Y_4}+\ldots\frac{L_{(M-1)M}}{Y_{(M-1)}Y_{(M)}}}} \tag{11}$$

In equation 11, n is Manning's roughness coefficient, Q is streamflow, h is elevation of water surface, at the respective sections above a common datum, Δhv is upstream velocity head minus the downstream velocity head, L is distance between two cross sections, Y is $AR^{2/3}$; A is the cross sectional area of the transect; R is the hydraulic radius; and K is a coefficient taken to be zero for contracting reaches and 0.5 for expanding reaches.

Flow Analysis

The hydrodynamic component of the sediment transport model was based on a stage-streamflow relation. For the 730-day simulations (2001–02 calendar year), daily mean streamflows from the Plainwell streamgage (04106906) were used as the upstream-boundary condition and stage data from Allegan streamgage (04107850) were used as the downstream boundary condition. Continuity was checked throughout the model to ensure that mass was being conserved. The model did indeed conserve mass in the study reach during the entire simulation period under varying flow conditions (fig. 4). A tolerance of ±3-percent discrepancy in mass conservation is typically acceptable for most models (U.S. Army Corps of Engineers, 1997).

Also, the simulated flow rates were compared to the six observed flow measurements, which were recorded near the 15th Street Bridge (below the Otsego City Dam) during 2001 and 2002 (fig. 5). In the model simulations, this location is near transect 75 (fig. 2).

The observed and simulated flows are in close range, but the overall residuals show a 3- to 4-percent bias towards the measured flows. The measured flows were higher than the simulated flows because of the flow input from the Gun River, which is a tributary to the main Kalamazoo River and is approximately 800 meters upstream from the Otsego City Dam (fig. 2). No continuous streamflow record available for the Gun River; however, synoptic flow measurements done previously show approximately a 3- to 5-percent flow contribution to the Kalamazoo River. The effect of the Gun River on the streamflows and sediment transport rates in the Kalamazoo River study area is minimal, because the Gun River basin is approximately 296 km^2 as compared to the 3,963 km^2 Kalamazoo River study area basin.

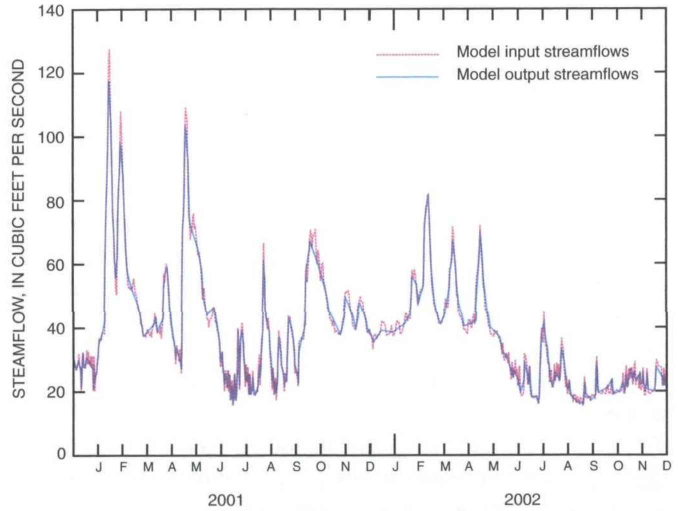


Figure 4. Comparison of model-input streamflows recorded at the Plainwell streamgage and model-simulated streamflows to check for continuity.

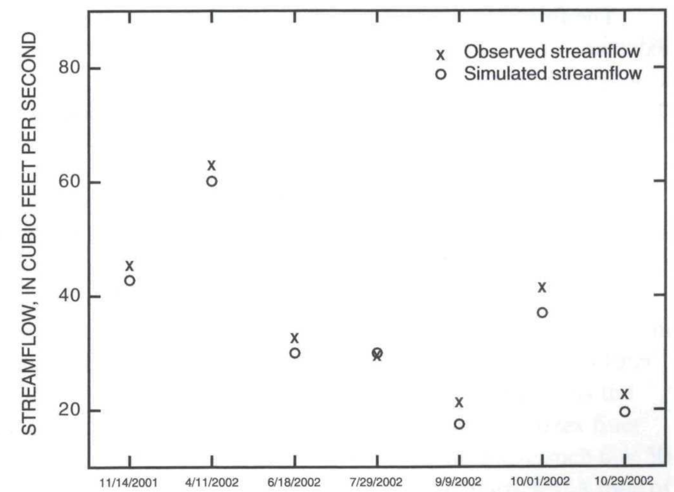


Figure 5. Simulated and observed streamflows. Measurements made at the 15th Street Bridge below Otsego City Dam, which is near transect 75 in the model simulation.

Sediment-Transport Model Calibration

Calibration is the process of adjusting model parameters to obtain best fit of the simulation results to the observed field data. The process can be completed manually using engineering judgment by repeatedly adjusting parameters, computing, and inspecting the goodness-of-fit between the simulated and observed data. However, significant efficiencies can be achieved with an automated procedure.

The quantitative measure of the goodness-of-fit is the objective function. An objective function measures the degree of variation between the simulated and observed values. It is equal to zero if the values are identical. A minimum objective function is obtained when the parameter values are best able to reproduce the observed values. In making adjustments, the modeler should always keep in mind that these parameters represent some physical process; therefore, there should be reasonable physical bounds or constraints beyond which they should not be adjusted.

Sediment-transport variables consist of suspended-sediment concentration and bedload transport, combined as total load. The model could not be calibrated to total load because of the small number of field collected bedload samples. Because sufficient field data for suspended sediment were available, the model was calibrated to suspended load. Sediment transport model calibration can be achieved with the most commonly available type of sediment-transport data, which is most often the concentration of suspended sediment (Simons and others, 2000).

Root mean square error (RMSE) was used as an objective function for measuring the goodness-of-fit between the simulated and observed suspended-sediment transport rates. The field data used for calibration were collected near the Allegan streamgage (transect 128), channel 15, during January 1, 2001 through December 31, 2001. In the model, the term γ_o of equation 10 from McLean (Bennett, 2001) was used a calibration parameter. This coefficient sets the concentration at the base of the suspended transport layer and provides the only direct mechanism within the model to calibrate or adjust predicted suspended-sediment transport rates to match the observed rates. The McLean coefficient is a dimensionless parameter.

The McLean coefficient was adjusted manually for each model run, with a constraint limit set between 0.0013 and 0.008. The specified range for the McLean coefficient was chosen based on results obtained from model runs outside the chosen range. Model runs outside the chosen range of McLean coefficient show oscillations in the model results and, in some cases, no convergence of the model solution. After each model run with a specified McLean coefficient, RMSE was computed using simulated and observed suspended-sediment rates. The values of RMSE obtained along with specified values of the McLean coefficient for each model run are shown in figure 6.

The minimum value of objective function (RMSE) achieved was 0.0028 using a McLean coefficient of 0.004. The residuals obtained from the minimized objective function value are shown in figure 7. Analyses of the residual plot and streamflow hydrograph show a slight bias in the model results at high-flow (flows higher than 75 m^3/s); this means that the model-simulated suspended-sediment transport rates are higher compared to the observed data (fig. 8). However, the overall calibrated model results show close agreement between simulated and measured values of suspended sediments.

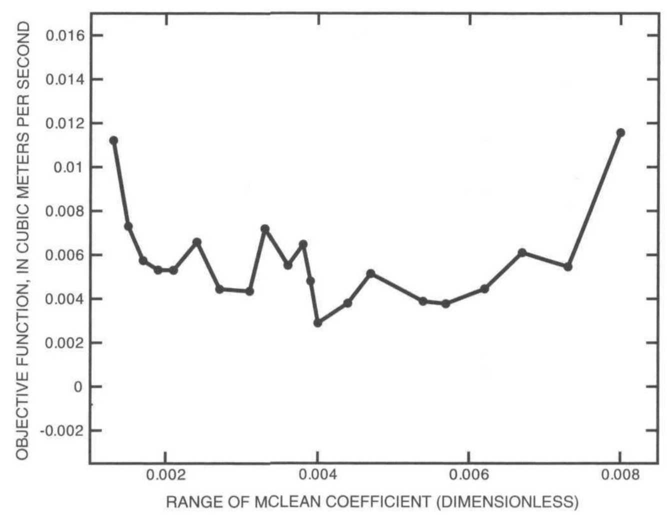


Figure 6. Minimized objective function for McLean coefficient as a model calibration parameter.

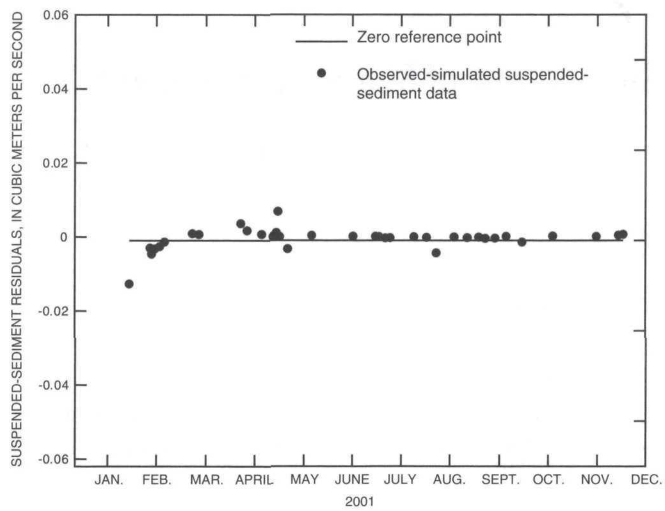


Figure 7. Calibrated model residuals (observed minus simulated), achieved with a McLean coefficient value of 0.004.

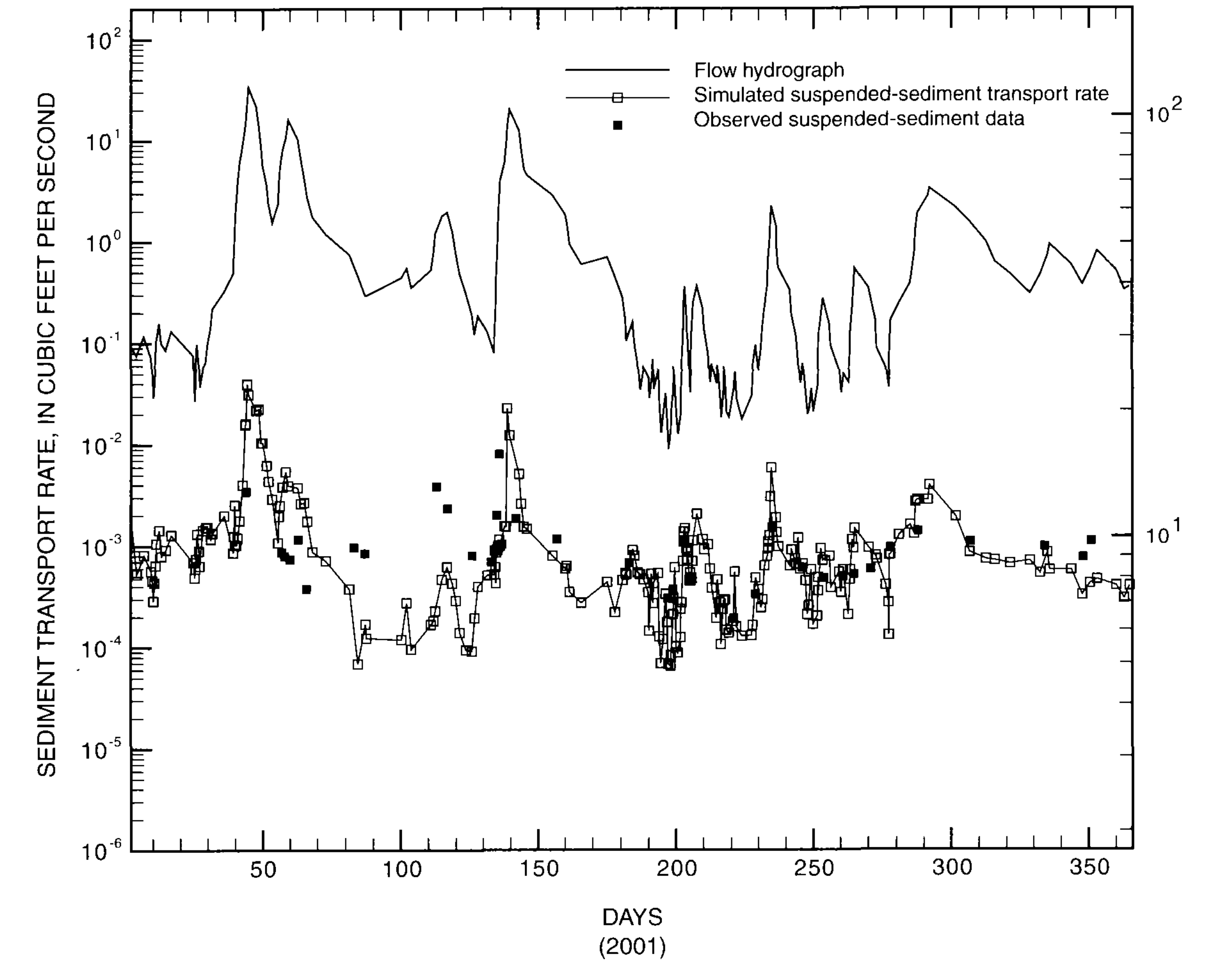


Figure 8. Observed and simulated suspended sediment transport rates after calibration. (Note that y-axes are in log scale.)

Simulations of Sediment Transport

The model results are based on the following three scenarios:

1. Sediment transport simulations for 730 days (Jan. 2001 through Dec. 2002) with existing dam structures.
2. Sediment transport simulations based on flows from the 1947 flood at the Kalamazoo River with existing dam structures, and
3. Sediment transport simulations based on flows from the 1947 flood at the Kalamazoo River with dams removed.

Sediment-Transport Simulations with Existing Dam Structures

For this scenario, the model runs for a total period of 730 days (Jan. 1, 2001 through Dec. 31, 2002). The results obtained were analyzed in three categories: (1) total volume and size distribution of instream sediments (conditions before simulations), (2) sediment erosion and deposition rates during the simulation period, and (3) significant changes observed in sediment bed elevations and d_{50}s during the simulation period.

Total Volume and Median Size Distribution of Instream Sediment

The model computes the sediment volume between model transects, using the "average end area" formula; that is, the volume referenced to a particular elevation for any section 2 through n of a particular channel is determined by computing the areas for each section between the specified nonerodible boundaries (the banks) and delimited by the (horizontal) bedrock elevation and the horizontal surface at the given elevation. Once the corresponding areas at a particular elevation are determined for each of the bounding sections, the areas are averaged and then multiplied by the straight-line distance between the centroids of the two sections to obtain the volume. At a particular time step, volumes reported for channel segments are

obtained by summing the volumes for the 2nd through nth cross-section (section 1 has no volume associated with it) applicable to the then current bed elevation at each section. Physical volumes are computed and sediment solids volume is assumed to be 70 percent (porosity = 0.3) of the physical volume.

In this report, details regarding the thickness of the sediment layer, sediment d_{50}s, and sediment volumes in the study reach are shown for the backwater reach of each impoundment. This is because most of the instream sediments in the study area are present in the backwater section of each impoundment; furthermore, significant bed-elevation changes that are due to variable flow were noticeable in these sections.

The total volume and median size of sediments in the backwater section of each impoundment is listed in table 1.

Sediment Erosion and Deposition Rates During the Simulation Period

In this section of the report, sediment transport results are arranged on the basis of magnitude of flow rates that triggered major changes in sediment erosion or deposition rates during the simulation period. Analysis of the model results shows that significant sediment erosion from the study reach occurs at flows higher than 55 m^3/s. Similarly, significant sediment deposition occurs during low to average flow (monthly mean flows between 25.49 and 50.97 m^3/s), after a high-flow event until the system reaches equilibrium.

During the 730-day simulation, high-flow events occur February 9 to March 8, 2001 (maximum streamflow, 117 m^3/s), May 14 to June 8, 2001 (maximum streamflow, 104 m^3/s), October 14 to November 4, 2001 (maximum streamflow, 68 m^3/s), and March 3 to March 18, 2002 (maximum streamflow, 81 m^3/s). During these four high flow events, model results show a total sediment erosion of approximately 88,890 m^3, 7,400 m^3, 3,600 m^3, and 3,600 m^3 respectively, from the study reach. Transport rates and associated volume errors are listed in table 2.

Deposition is dominant in the study reach for a short time after the high-flow event in March 2001. During that period, the average sediment-supply rate into the study reach is approximately 71 Mg/d, and the total sediment loss from the system is approximately 57 Mg/d. As a result, a total sediment load of approximately 14 Mg/d is deposited. Similarly, the average sediment-deposition rates are in the range of 4 to 15 Mg/d after the June and November 2001 and March 2002 high-flow events. If the flow continues to stay in the low to average range then the system shifts towards equilibrium. This results in a balancing effect between sediment deposition and erosion rates.

The total simulated volume of sediment eroded at the end of 2001 is approximately 164,000 m^3. And the total volume of sediment eroded at the end of year 2002 is approximately 12,200 m^3. Higher erosion rates for 2001 are due to high-magnitude flow rates during that year as compared to flow rates in 2002 (fig. 8). An assessment of the individual reaches in the study area at the end of 730 days shows that degradation is significant in channels 1, 8, and 9 (fig. 2). From these channels, a total volume of approximately 45,410 m^3, 37,650 m^3, and 57,230 m^3, respectively of instream sediments are eroded during the 730-day simulation period.

Table 1. Volume of instream sediment in the backwater section of each dam.

Location	Sediment layer thickness (meter)	Range of d_{50}s of the top sediment layer (millimeter)	Volume of sediment present (cubic meter)
Upstream from the Plainwell Dam to a distance of 944 meters	0 to 3.7	0.0625 to 3.720	76,062
Upstream from the Otsego City Dam to a distance of 982 meters	0 to 1.8	0.0625 to 1.609	132,172
Upstream from the Otsego Dam to a distance of 2,020 meters	0 to 2.7	0.0625 to 2.723	257,568
Upstream from the Trowbridge Dam to a distance of 3,250 meters	0 to 4.6	0.117 to 1.108	750,757

Table 2. Simulated sediment transport rates during the high-flow events between January 2001 and December 2002.

[m^3, cubic meter; m^3/s, cubic meter per second; Mg/d, megagram per day]

Time of the year	Peak flow rates (m^3/s)	Net erosion from the study reach (m^3)	Range of transport rates (m^3/s)	Range of transport rates (Mg/d)
Feb. 9 to Mar. 4, 2001	117	88,890	0.00099 to 0.10580	206 to 24,224
May 15 to June 6, 2001	104	7,400	0.00027 to 0.00892	63 to 2,041
Oct. 14 to Nov. 4, 2001	68	3,600	0.00007 to 0.00120	15 to 274
Mar. 3 to Mar. 26, 2002	81	3,600	0.00004 to 0.00501	8 to 1,146

Sediment deposition is substantial in channels 13 and 14, which are the most downstream channels in the study section (fig. 2). In channels 13 and 14, a total volume of approximately 31,000 and 21,000 m^3 of sediments are deposited during the 730-day simulation period. Total sediment transport rates during the simulation period 2001–02 are shown in figure 9.

Significant Changes in Sediment Bed Elevations and Size Composition During the Simulation Period

The model keeps track of the bed-elevation changes and sediment-size composition (d_{50}) during simulation at each cross section. Model results show significant changes in bed elevations during high flows such as during February 9 to March 8, 2001 (maximum streamflow 117 m^3/s), May 14 to June 8, 2001 (maximum streamflow rate 104 m^3/s), October 14 to November 4, 2001 (maximum streamflow rate 68 m^3/s), and March 3 to March 18, 2002 (maximum streamflow rate 81 m^3/s). Simulation results show that scour or degradation occurs in channel segments upstream from the Plainwell, and Otsego City Dams. Deposition occurs in channel 13 and 14, which are the downstream channels (fig. 2).

Some of the channel transects that show significant changes in bed elevation during the simulation period include the following:

- In channel 5, cross section 27, which is at the junction of channels 3 and 4, the bed scours about 0.8 m (2.62 ft) during the February 9 to March 8, 2001, high flows. Bed armoring occurs during the simulation period. Bed armoring is a process during sediment transport in which a layer of coarse material completely covers the streambed and protects the finer material beneath it from being transported (Yang, 1996). Armoring is evident from the sediment d_{50} size, which is in the range of 5 mm by the end of simulation period (fig. 10).

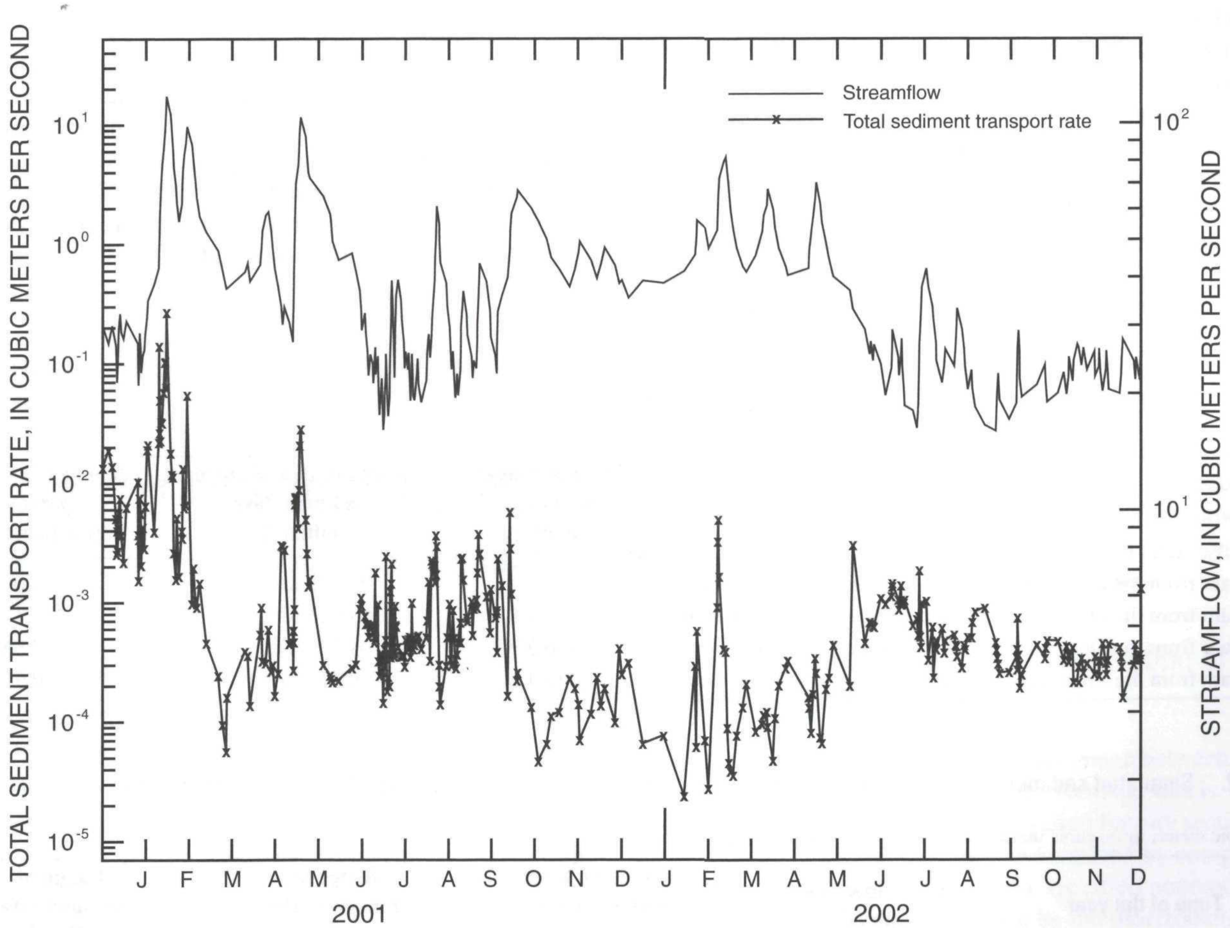


Figure 9. Simulated total sediment-transport rates during the simulation period January 2001 to December 2002. (Note that y-axes are in log scale.)

- In channel 11, transect 50, which is where channel 9 and 10 form a junction and flows into channel 11 (fig. 2), degradation of approximately 0.8 m (2.64 ft) is evident during the high flows of February 9 to March 8, 2001 (fig. 11). There is slow aggradation in this transect during the rest of the simulation period.
- In channel 11, cross section 64, aggradations or degradation occurs in response to the changes in flow rates. The bed scours about 0.4 m (1.31 ft) during high flow. During low to average flow the bed starts building up again (aggrades) (fig. 12).
- No degradation occurs in transect 80 and 88, which are in channels 12 and 13. These two transects are highly depositional during the entire simulation period (figs. 13 and 14).
- Transect 93, in channel 13, shows significant changes in sediment-bed elevations and d_{50} in response to the changing flow conditions (fig. 15).

The bed-elevation field data collected during the transect surveys were used as an input into the model. No further bed-elevation data were collected to validate the simulated elevations at the end of the study period.

Sediment-Transport Simulation Results, Using Flows From the 1947 Flood with Existing Dam Structures and Dams Removed

The highest peak flow recorded in the Kalamazoo River occurred during the 1947 flood (peak flow 235.2 m^3/s). Sediment transport simulations based on the 1947 flood hydrograph provide an estimate of sediment transport rates under maximum flow conditions. These scenarios can be used as an assessment of the sediment load that may erode from the study reach at this flow magnitude during a dam failure.

For the 1947 flood scenarios, the model uses the same network description file as that used for the January 2001 to December 2002, simulation. Fixed boundary conditions such as the transect geometry, bed elevations, and sediment-size distribution are the same in all model scenarios. The flows and stages used in the 1947 flood scenarios were derived from the Comstock and Fennville gage records. The estimated sediment-supply rates into the study reach are based on the field data collected near the Plainwell gage at high flow.

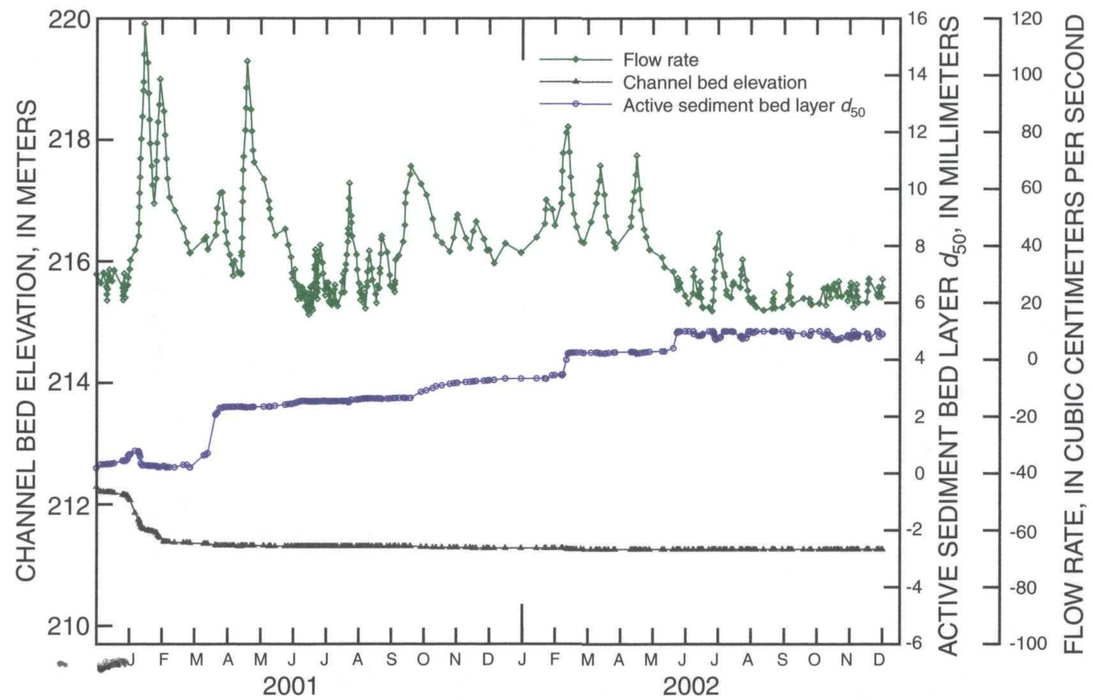


Figure 10. Changes in bed elevations and sediment d_{50} (median bed-sediment size, such that 50 percent of the particles are finer) during the 730-day model simulations for channel 4, cross section-27.

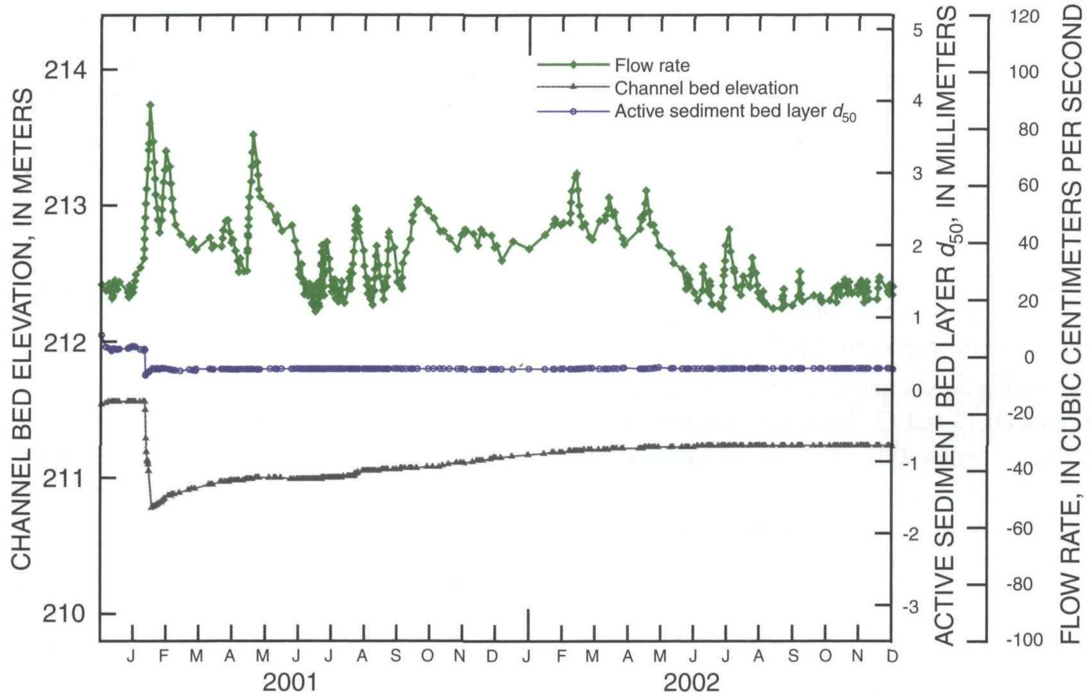


Figure 11. Changes in bed elevations and sediment d_{50} (median bed-sediment size, such that 50 percent of the particles are finer) during the 730-day model simulations for channel 9, cross section-50.

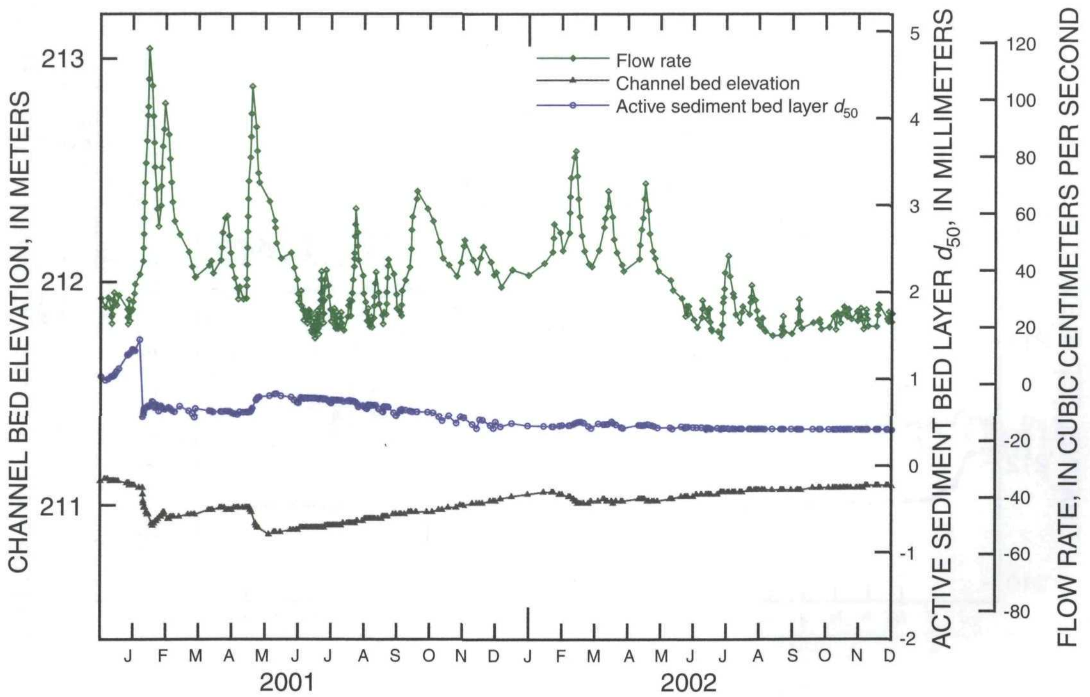


Figure 12. Changes in bed elevations and sediment d_{50} (median bed-sediment size, such that 50 percent of the particles are finer) during the 730-day model simulations for channel 11, cross section-64.

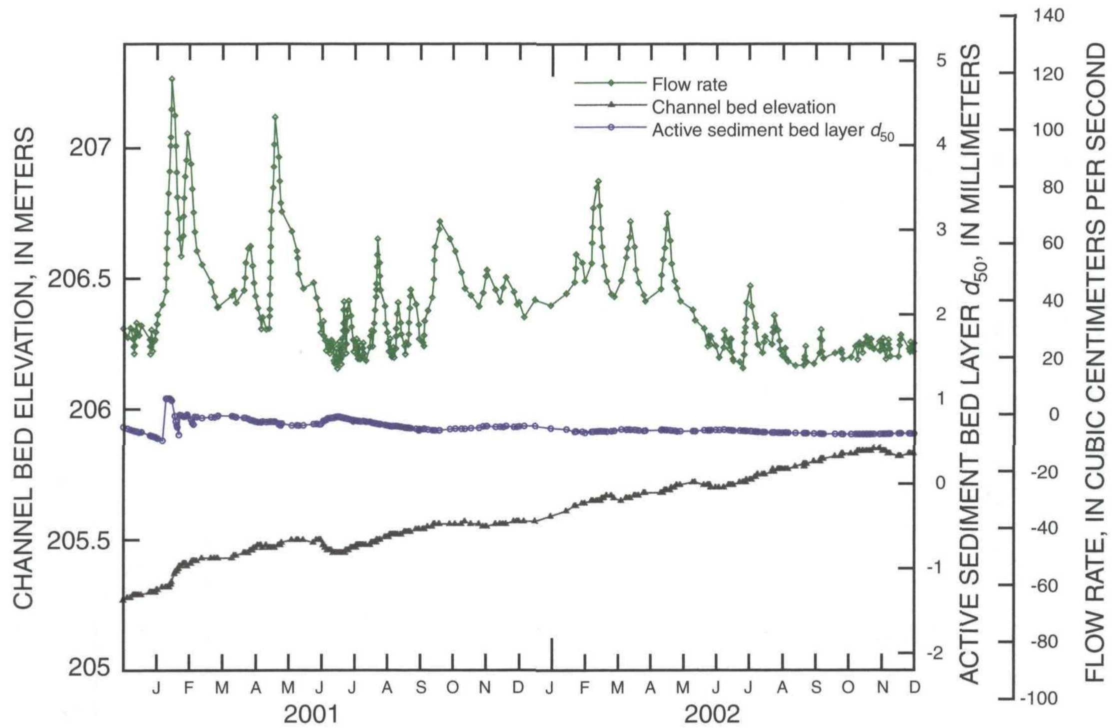


Figure 13. Changes in bed elevations and sediment d_{50} (median bed-sediment size, such that 50 percent of the particles are finer) during the 730-day model simulations for channel 12, cross section-80.

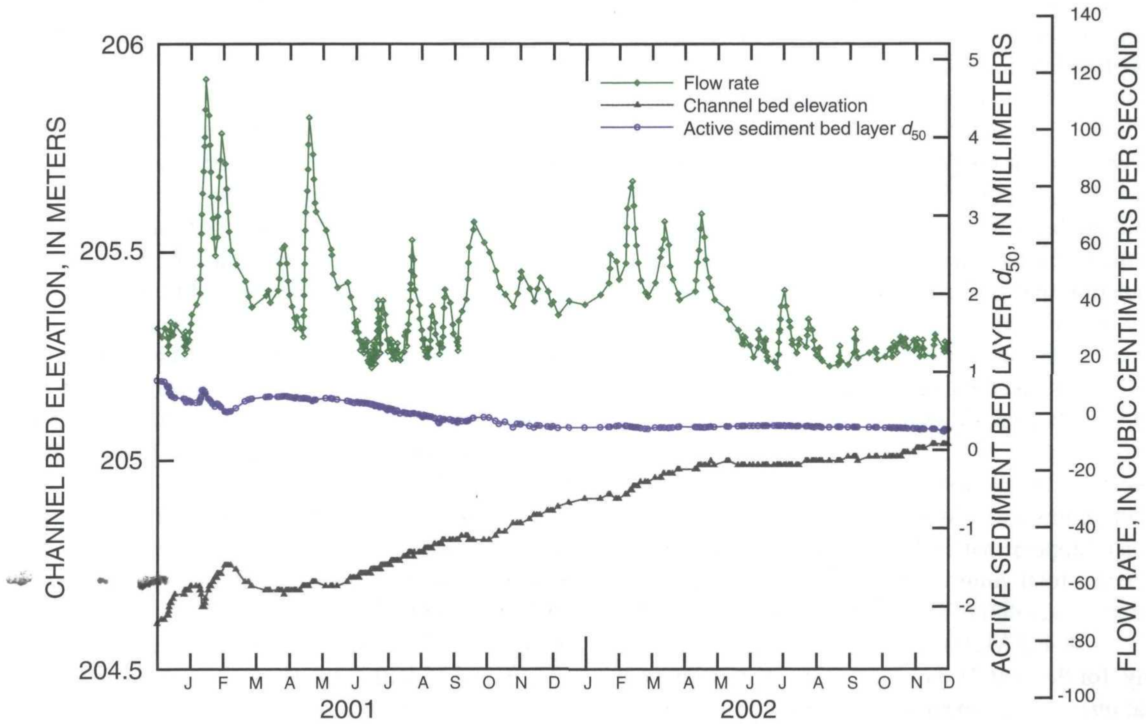


Figure 14. Changes in bed elevations and sediment d_{50} (median bed-sediment size, such that 50 percent of the particles are finer) during the 730-day model simulations for channel 13, cross section-88.

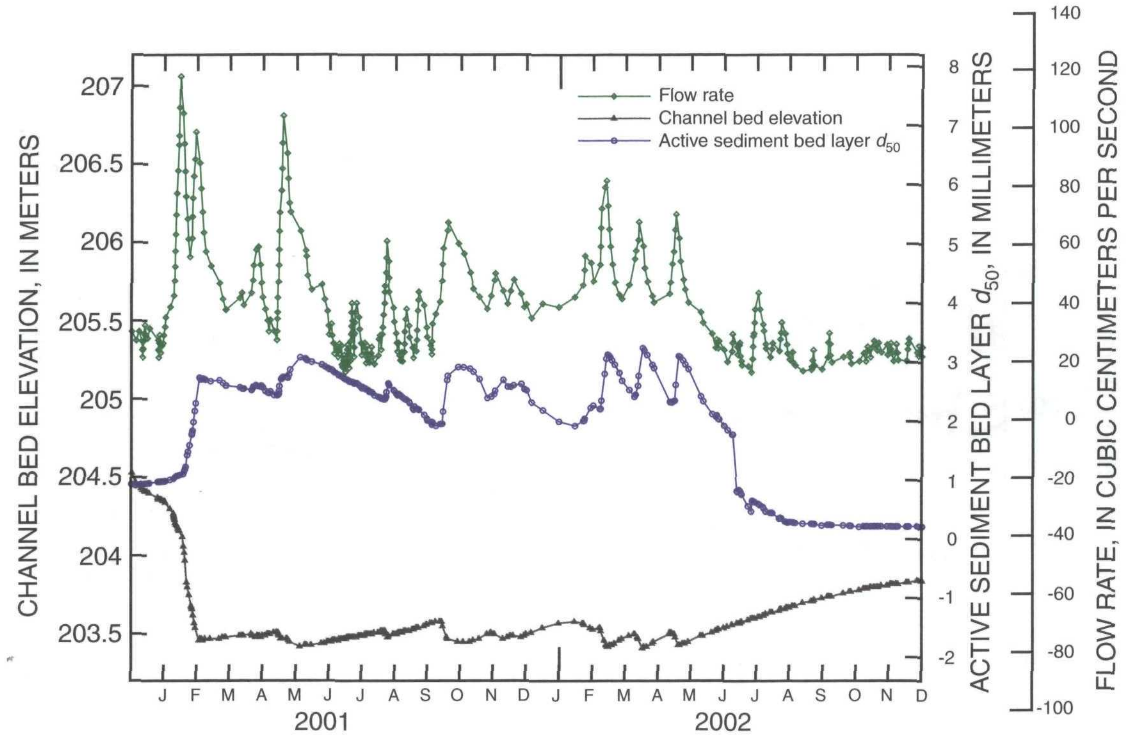


Figure 15. Changes in bed elevations and sediment d_{50} (median bed-sediment size, such that 50 percent of the particles are finer) during the 730-day model simulations for channel 13, cross section-93.

During simulations, the model routes the 1947 flood hydrograph through the study reach under two different conditions: (1) 1947 flood with existing or current dam structures; and (2) 1947 flood with no dam structures in the study section. The main difference between the existing-dams and dam removed scenarios is that the former considers all the current dam structures present in the study section during the simulation period, but the latter assumes that none of the dam structures exist in the study section during the simulation period.

The simulation span 60 days, a period based on to simulate the before and after effects of 1947 flood in the Kalamazoo River. The flood hydrograph rises at day 10, peaks at 235.2 m^3/s on day 15, and then recedes at day 21. It peaks again at day 31 and 43 with peak flows of 83 m^3/s and 77 m^3/s, respectively (figs. 16 and 17).

Analyses of the simulation results for the first 21 days with the existing-dams scenario show a total instream sediment loss or erosion of approximately 127,600 m^3 from the entire study reach, with a total volume error of 100 m^3. The peak sediment-transport rate ranges from 0.00165 m^3/s (377 Mg/d) to 0.16800 m^3/s (38,465 Mg/d).

Similarly, for the first 21 days during the dams removed scenario, total instream sediment loss or erosion is approximately 152,700 m^3 from the entire study reach, with a total volume error of 171 m^3. The peak transport rate during this time is in the range of 0.00064 m^3/s (146 Mg/d) to 0.17660 m^3/s (40,434 Mg/d) (table 3).

Locally weighted regression smoothing (LOWESS) function was applied to simulation results of both scenarios. The objective of this exercise was to fit a curve to the data point locally, so that at any point the curve at that point depends only on the observations at that point and some specified neighboring points. This was done with the "S–PLUS 2000" statistical program (Mathsoft Engineering and Education, Inc., 1999). During the dams removed scenario the LOWESS curve indicates a steep downtrend with high sediment transport rates during the first 21 days (fig. 18). In comparison, the LOWESS curve for the existing-dams scenario shows a smooth transition of sediment transport rates in response to the change in streamflow (fig. 19).

For the existing-dams scenario, simulation results show significant levels of degradation from channels 1, 4, 8, and 9, with a total degradation of approximately 42,190 m^3, 19,570 m^3, 28,020 m^3, and 73,400 m^3, respectively during the 60-day period. Aggradation or deposition occurs in channels 12, 13, and 15 with total deposited volumes of approximately 8,599 m^3, 21,160 m^3, and 5,832 m^3, respectively. Channels 12 and 13 are between the Otsego City and Otsego Dams, and channel 15 is downstream from the Trowbridge Dam.

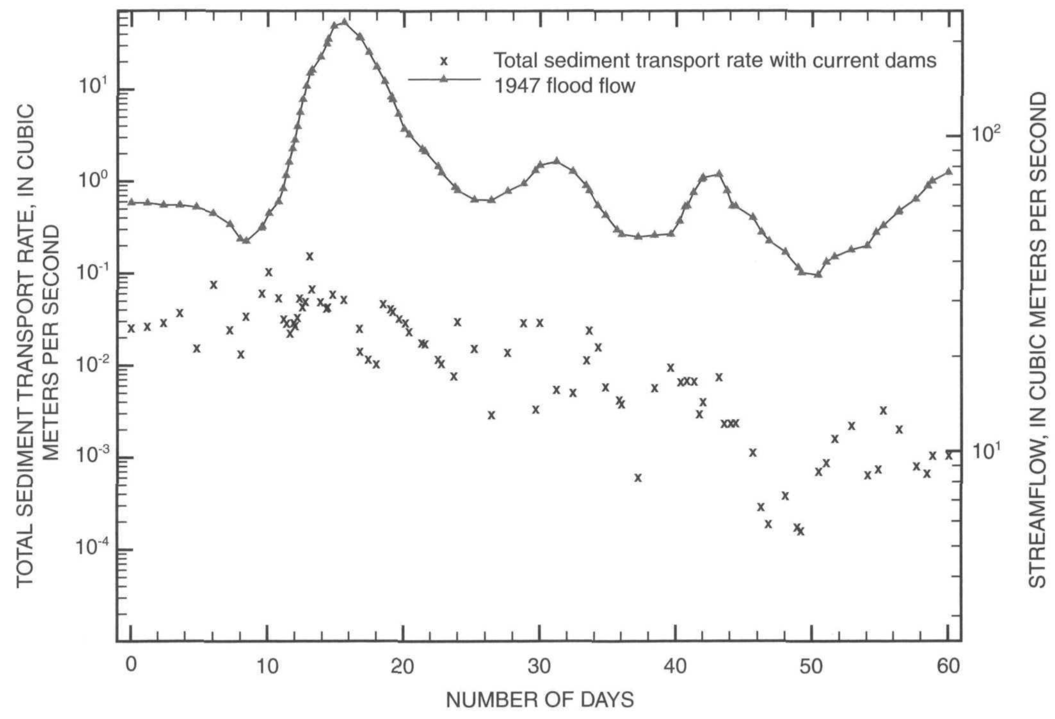


Figure 16. Simulated total sediment transport rates for 1947 flood with current dam structures. (Note that y-axes are in log scale.)

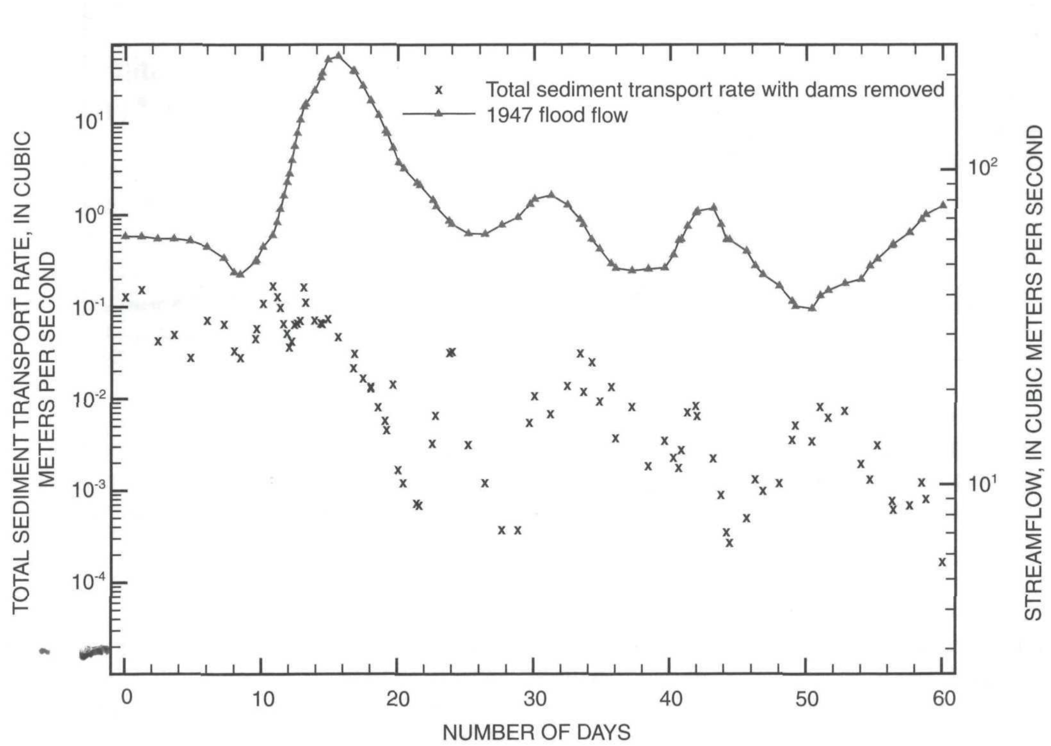


Figure 17. Simulated total sediment transport rates for 1947 flood with dams removed conditions. (Note that y-axes are in log scale.)

Table 3. *Simulated sediment transport rates during the 1947 flood simulations.*

[m^3, cubic meter; m^3/s, cubic meter per second; Mg/d, megagram per day]

Scenarios and associated timeframes	Peak flow rates (m^3/s)	Net erosion from the study reach (m^3)	Range of transport rates (m^3/s)	Range of transport rates (Mg/d)
		With existing dams		
0 to 21 days	235	127,600	0.00165 to 0.16800	377 to 38,465
22 to 60 days	83	32,300	0.00050 to 0.01461	113 to 3,345
		With dams removed		
0 to 21 days	235	152,700	0.00064 to 0.17660	146 to 40,434
22 to 60 days	83	24,200	0.00046 to 0.09876	105 to 22,612

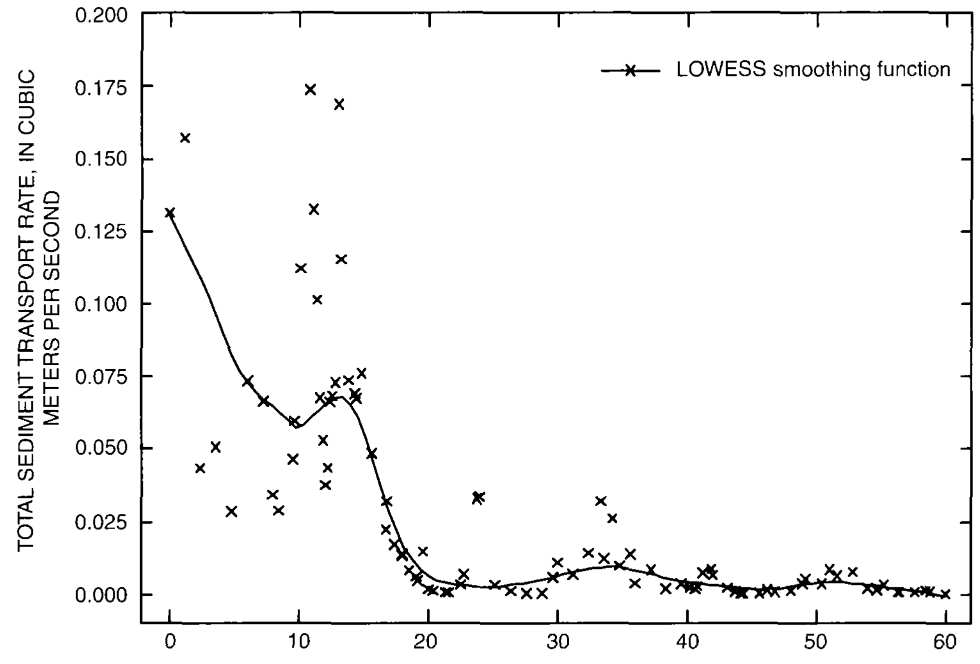


Figure 18. Application of locally weighted regression smoothing (LOWESS) function to simulation results of 1947 flood flow with dams-removed scenario. This indicates a steep downward trend with high sediment transport rates during the first 21 days. (LOWESS span of 0.2 was used for smoothing.)

For the dam removed scenario, simulation results show that degradation is significant in channels, 1, 4, 8, and 9, with total degradation of approximately 43,490 m^3, 20,320 m^3, 26,190 m^3 and 72,320 m^3, respectively, during the 60-day period. Aggradation occurs in channels 12, 13 and 15, with volumes of approximately 22,010 m^3, 19,300 m^3, and 8,967 m^3, respectively. Total sediment transport rates for the existing-dams and dams removed scenarios are shown in figures 16 and 17.

Channel 14 becomes depositional during the dams removed scenario. Approximately 5,914 m^3 of instream sediments were eroded during the existing-dams scenario as compared to the 581 m^3 of instream sediment eroded during the dams removed scenario.

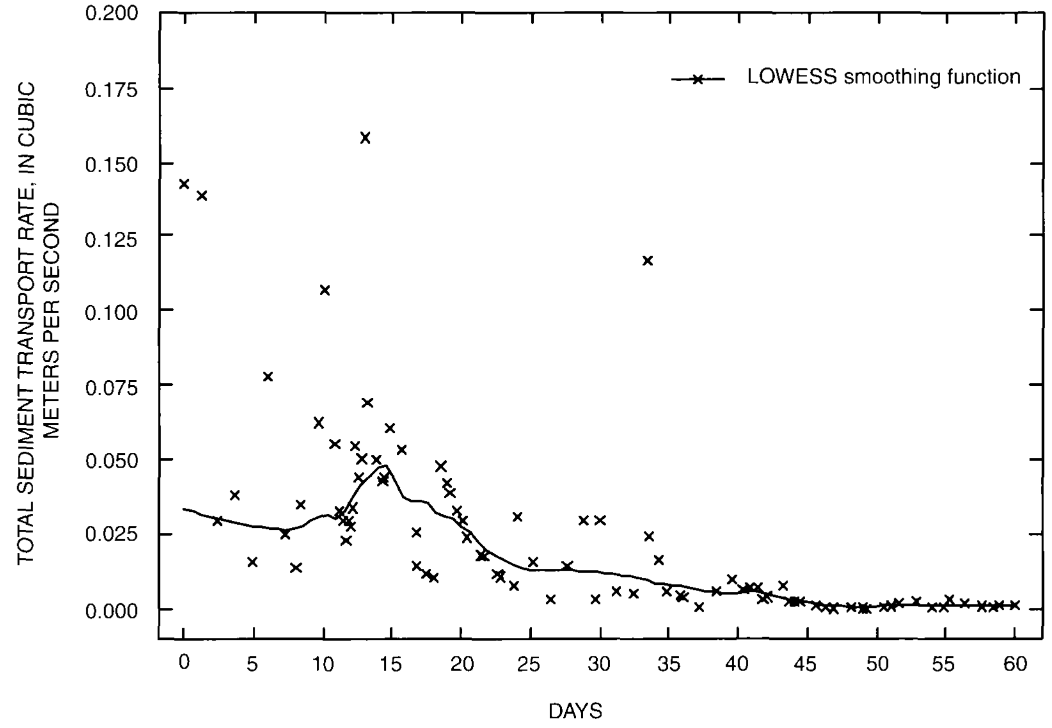


Figure 19. Application of locally weighted regression smoothing (LOWESS) function to simulation results of 1947 flood flow with existing-dams scenario. This shows a smooth transition of sediment transport rates in response to the change in streamflow. (LOWESS span of 0.2 was used for smoothing.)

Assumptions and Limitations of the Sediment-Transport Model

Before making any decisions based on the model results, it is important to consider the following assumptions and limitations of the model.

- The different scenarios generated by the model should be considered as a tool to assess pre- and post-dam-removal conditions. The reader should be aware that "dam removal" in the modeling scenarios does not mean a "dam breach:" instead, it is the complete removal of a nonerodible structure (for example, a sharp-crested weir with a defined geometry) during simulation. Therefore, the model results produced for the "dams-removed" scenario shows the changes in the hydraulics of the flow and the associated sediment transport mechanics resulting from the removal of a nonerodible structure rather than an actual dam failure.
- Elimination of some of these reaches from the model could theoretically generate high erosion rates in the modeled reaches due to excessive shear stress produced by the flow, since the flow is routed through the selected reaches as compared to the flow distribution in the existing natural system. This potential bias could affect sediment deposition and erosion rates produced by the model.
- SEDMOD computes the volume error for the pertinent time step (reporting day stated in the file) by taking the difference between the net input of sediment for the entire simulation period up to the reporting day and the net sediment volume accumulated in all the channels in the network up to that day. The net input of sediment for the reporting period is the sum of the incoming sediment volumes since the beginning of the simulation and up until that time for all channels that enter the network, minus the sum of all of the sediment volumes leaving the network during the period. Ideally, net input equals all of the sediment volume accumulated in all of the network channels up to the reporting period. The volume error reported, then, is the difference in cubic meters between the net input volume and the computed sediment accumulation for the network (table 4). It is a measure of the accuracy of the model in mass conservation. The volume errors reported can be magnified by round-off error, because the model tracks sediment volumes using single-precision variables. Round-off errors will occur if varying digits precede the values of the x- and y-coordinates of the end points of the transect range lines.

Table 4. Sediment mass-balance errors reported by the model during simulation.

[m^3, cubic meters]

Scenarios and associated timeframe	Net erosion from the study reach (m^3)	Total volume errors (m^3)
Jan. 2001 to Dec. 2002 with existing dam structures:		
Feb 9 to Mar 4, 2001	88,890	1,080
May 15 to June 6, 2001	7,400	526
Oct. 14 to Nov. 4, 2001	3,600	146
Mar. 3 to Mar. 26, 2002	3,600	32
1947 flood with existing dam structures:		
0 to 21 days	127,600	100
22 to 60 days	32,300	393
1947 flood with no dam structures:		
0 to 21 days	152,700	114
22 to 60 days	24,200	404

Summary and Conclusions

The four dams on the Kalamazoo River between the cities of Plainwell and Allegan, Mich., are in varying states of disrepair and are under consideration by MDEQ and USEPA for future removal to restore the river channels to pre-dam conditions. Sediments associated with these impoundments are contaminated with polychlorinated biphenyls (PCB) (Blasland, Bouck & Lee, Inc., 1994). Therefore, removal of these dams, either by catastrophic flood or engineered deconstruction, would mobilize the contaminated sediments and potentially damage the natural aquatic habitat downstream. The USGS in cooperation with the USEPA and MDEQ did this study, to identify sediment characteristics, monitor sediment transport, and predict sediment resuspension and deposition under varying hydraulic conditions.

The mathematical sediment transport model SEDMOD was used to simulate streamflow and sediment transport on the Kalamazoo River between the cities of Plainwell and Allegan, Mich. The steady-state one-dimensional model uses time-varying hydrographs to compute the resultant scour and fill at any given location in the river reach. Different model scenarios were generated to assess sediment transport under varying hydraulic conditions.

Analyses of the model results show that the Kalamazoo River sediment transport mechanism is in a dynamic-equilibrium state. Model simulations indicate significant sediment erosion from the study reach at flow rates higher than 55 m^3/s. Similarly, significant sediment deposition occurs during low to average flows (monthly mean flows between 25.49 m^3/s and 50.97 m^3/s) after a high-flow event until the system reaches equilibrium.

During the 730-day simulation from January 2001 to December 2002, high-flow events occur February 9 to March 8, 2001 (maximum streamflow 117 m^3/s.), May 14 to June 8, 2001 (maximum streamflow, 104 m^3/s), October 14 to November 4, 2001 (maximum streamflow, 68 m^3/s), and March 3 to March 18, 2002 (maximum streamflow, 81 m^3/s). During these four flow events, model results show a total sediment erosion of approximately 88,890 m^3, 7,400 m^3, 3,600 m^3, and 3,600 m^3 respectively, from the study reach.

Deposition is dominant in the study reach for a short time after the high-flow event in March 2001. During that period, the average sediment-supply rate into the study reach is approximately 71 Mg/d, and the total sediment loss from the system is approximately 57 Mg/day. As a result, a total sediment load of approximately 14 Mg/d is deposited. Similarly, the average sediment-deposition rates are in the range of 4 to 15 Mg/d after the June and November 2001 and March 2002 high-flow events. If the flow continues to stay in the low to average range then the system shifts towards equilibrium. This results in a balancing effect between sediment deposition and erosion rates.

Sediment transport simulations using the 1947-flood hydrograph for the first 21 days with the existing-dams scenario show a total instream sediment loss or erosion of approximately 127,600 m^3 from the entire study reach, with a total volume error of 100 m^3. The peak transport rate ranges from 0.00165 m^3/s (377 Mg/d) to 0.16800 m^3/s (38,465 Mg/d).

Similarly, for the first 21 days during the dams-removed scenario, the simulation shows a total instream sediment loss/erosion of approximately 152,700 m^3 from the entire study reach, with a total volume error of 171 m^3. The peak transport rate during this time is about 0.00064 m^3/s (146 Mg/d) to 0.17660 m^3/s (40,434 Mg/d).

The 1947 flood-flow simulations show approximately 30,000 m^3 more instream sediment erosion for the first 21 days of the dams-removed scenario than for the existing-dams scenario, with the same initial conditions for both scenarios. Application of a locally weighted regression smoothing (LOWESS) function to simulation results of the dams-removed scenario indicates a steep downtrend with high sediment transport rates during the first 21 days. In comparison, the LOWESS curve for the existing-dams scenario shows a smooth transition of sediment transport rates in response to the change in streamflow. The high erosion rates during the dams-removed scenario are due to the absence of dams; in contrast, the presence of dams in the existing-dams scenario helps reduce sediment erosion to some extent.

The overall results of 60-day simulations for the 1947 flood show no significant difference in total volume of eroded sediment between the existing dams and dams-removed, because the dams in the study reach have low heads and no control gates. It is important to note that the existing-dams and dams-removed scenarios are run for only 60 days; therefore, the simulations take into account the changes in sediment erosion and deposition rates only during that time period. Over an extended period, more erosion of instream sediments would be expected to occur if the dams were not properly removed than under the existing conditions. On the basis of model simulations, removal of the dams would further lower the head in all the channels. This lowering of head could produce higher flow velocities in the study reach, which ultimately would result in accelerated erosion rates.

Acknowledgments

The authors thank Shari Kolak, Remedial Project Manager, Region 5, Superfund Divison (USEPA); and Paul Bucholtz, Environmental Quality Analyst (MDEQ). Todd King of Camp Dresser & McKee, Inc. provided technical support. In addition, the authors express their appreciation to the USGS personnel who participated in the collection and analysis of data and in the preparation and review of this report. Stephen Rheaume and Derrick Hubbell participated in the field data collection and provided a data set from which the model input files were built. Andreanne Simard did all the sieve analyses for the transect core samples. Denis Healy provided information regarding model input files and developed the network description file for the lower two dams. David Holtschlag helped describe the flow distribution in the braided reach of the Kalamazoo River, and Lori Fuller provided GIS support.

References Cited

Autodesk, Inc., 2003, User's guide AutoCAD LT: San Rafael, Calif., Autodesk, Inc., 341 p.

Barnes, H.H., 1967, Roughness characteristics of natural channels: U.S. Geological Survey Water-Supply Paper 1869, 213 p.

Bennett J.P., 1995, Algorithm for resistance to flow and transport in sand-bed-channels: Journal of Hydraulic Engineering, v. 121, no. 8, p. 578-590.

Bennett J.P., 2001, User's guide for mixed-sized sediment transport model for networks of one-dimensional open channels: U.S. Geological Survey Water-Resources Investigations Report 01-4054, 33 p.

Blasland, Bouck & Lee, Inc., 1994, Allied Paper, Inc./ Portage Creek/ Kalamazoo River Superfund site remedial investigation/ feasibility study: Technical memorandum 10, sediment characterization/Geo-statistical Pilot Study, v. I–III.

Blumer, S.P., Behrendt, T.E., Ellis, J.M., Minnerick, R.J., LeuVoy, R.L., and Whited, C.R., 2003, Water resources data, Michigan, water year 2002: U.S. Geological Survey Water-Data Report MI-02-1, 100 p.

Camp Dresser & McKee, 1999, Evaluation report of Plainwell Dam–Kalamazoo, Michigan, January 1999: Detroit, Mich., 5 p.

Chaudhry, M.H., 1993, Open channel flow: Englewood Cliffs, N.J., Prentice Hall, 483 p.

Doyle, M.W., Stanely, E.H., Harbor, J.M., and Grant, G.S., 2003, Dam removal in the United States—Emerging needs for science and policy: EOS, Transactions, American Geophysical Union, v. 84, no. 4, 3 p.

Edwards, T.K., and Glysson, D.G., 1999, Field methods for measurement of fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations TWI 03-C2, 89 p.

Federal Emergency Management Agency, 1999, National Dam Safety Program: accessed, April 04, 2003, at URL http://www.fema.gov/mit/ndspweb.htm

Mathsoft Engineering and Education, Inc., 1999, Guide to Statistics, S–Plus 2000, Data Analysis Product Division: Seattle, Wash., Mathsoft, Inc., v. 1, 638 p.

Mathsoft Engineering and Education, Inc., 2001, User's guide Mathcad 2001i: Cambridge, Mass., Mathsoft Engineering and Education, Inc., 505 p.

Quantative Environmental Analysis (QEA), 2001, Review of Kalamazoo River PCB fate model developed by Limno-Tech, Inc.: 106 p.

Rheaume, S.J., Rachol, C.M., Hubbell, D.L., and Simard, Andreanne, 2000, Sediment characteristics and configuration within three dam impoundments on the Kalamazoo River, Michigan: U.S. Geological Survey Water-Resources Investigation Report 02-4098, 51 p.

Simons, R.K., Canali, G.E., Anderson-Newton, G.T., and Cotton, G.K., 2000, Sediment transport modeling–calibration, verification, and evaluation: Journal of Soil and Sediment Contamination, v. 9, no. 3, p. 261–289.

Sturm, T.W., 2001, Open channel hydraulics: New York, McGraw-Hill Series in Water Resources and Environmental Engineering, 493 p.

U.S. Army Corps of Engineers, 1996, Water Council Infrastructure—National inventory of dams: Washington D.C., Federal Emergency Management Agency, CD-ROM.

U.S. Army Corps of Engineers, 1997, User's guide to RMA-2 WES (ver. 4.3): Vicksburgh, Miss., Waterways Experiment Station, 162 p.

Wiberg, P.L., 1987, Mechanics of bedload sediment transport: Seattle, Wash., University of Washington, Ph.D. dissertation, 132 p.

Yang, C.T., 1996, Sediment transport theory and practice: New York, McGraw-Hill Series in Water Resources and Environmental Engineering, 395 p.

Glossary

Bedload sediment Sediment that moves by saltation (jumping), rolling, or sliding in the flow layer just above the bed.

Critical shear stress Shear stress on the surface of the channel bottom just sufficient to cause sediment particles to start to move.

Dynamic-equilibrium Dynamic equilibrium refers to a condition in which the parts of a system are in continuous motion, but they move in opposing directions at equal rates so that the system as a whole does not change. In case of sediment transport it can be unidirectional but the system as a whole is balanced by the same magnitude of erosional and depositional forces.

Eddy diffusivity The exchange coefficient for the diffusion of a conservative property by eddies in a turbulent flow.

Fall velocity The velocity at which a particle will settle in still water.

Froude number The parameter that represents the gravitational effects in open channel flow. It is the ratio of the inertial and gravitational forces.

Hydraulic radius Channel cross-sectional area divided by the wetted perimeter.

Normal depth The depth associated with normal flow.

Porosity Measure of the volume of the voids per unit volume of the sediment.

Shear stress The force exerted by the flowing water on the stream bottom.

Shear velocity Measure of the shear force on the channel bottom, but has units of velocity.

Steady flow Mean flow velocity and mean flow depth is independent of the time variable.

Subcritical flow Flow with Froude number less than 1; flow at this state possesses relatively low velocity and high flow depth.

Supercritical flow Flow with Froude number greater than 1; flow possesses relatively high velocity and shallow depth.

Suspended sediment Sediment that stays in suspension for some extended period of time as a result of suspension by turbulence.

Transient flow Mean flow depth and mean flow velocity is independent of the position coordinate in the direction of flow.

Appendix 1. Suspended- and Bed-Sediment Data 2001–02 Kalamazoo River, Michigan

Table 1-1. Suspended-sediment data collected at the Main Street Bridge in the city of Plainwell.

Sampling date	Discharge (cubic meter/second)	Concentration (milligram/liter)	Transport rate (cubic meter/second)
February 14, 2001	124	44	0.002060
February 22, 2001	60	29	.000657
February 23, 2001	84	12	.000380
March 13, 2001	52	24	.000474
March 14, 2001	52	13	.000257
March 28, 2001	36	29	.000397
April 17, 2001	37	14	.000196
April 27, 2001	59	29	.000645
May 17, 2001	69	32	.000828
May 24, 2001	75	30	.000850
June 1, 2001	74	26	.000722
June 13, 2001	48	39	.000709
July 2, 2001	27	21	.000211
August 9, 2001	28	47	.000502
September 11, 2001	37	53	.000731
October 11, 2001	39	24	.000351
November 11, 2001	37	19	.000266
December 12, 2001	40	25	.000374
January 10, 2002	36	25	.000342
February 7, 2002	35	2	.000027
March 7, 2002	52	5	.000099
March 12, 2002	76	10	.000285
March 26, 2002	43	6	.000098
April 11, 2002	61	8	.000185
April 16, 2002	61	18	.000412
May 29, 2002	37	19	.000262
June 18, 2002	31	25	.000289
July 10, 2002	31	25	.000289
July 29, 2002	34	47	.000598
August 20, 2002	28	28	.000299
September 9, 2002	19	20	.000140
October 7, 2002	19	19	.000139
October 29, 2002	21	33	.000261
November 19, 2002	23	11	.000094
December 12, 2002	20	16	.000120

Table 1-2. Bed-load sediment data collected at the Main Street Bridge in the city of Plainwell.

Sampling date	Discharge (cubic meter/second)	Weight of the sample (gram)	Loading rate (grams/second)	Transport rate (cubic meter/second)
February 14, 2001	124	399.2	0.066533	0.0000263
February 22, 2001	59	99.2	.016532	.0000065
March 13, 2001	52	52.6	.008768	.0000035
March 28, 2001	38	50.9	.008480	.0000034
May 25, 2001	68	490.5	.081743	.0000323
August 9, 2001	20	10.7	.001783	.0000007
October 11, 2001	42	23.2	.003865	.0000015
November 15, 2001	42	106.4	.017735	.0000070
December 12, 2001	39	8.3	.001387	.0000005
January 10, 2002	38	15.0	.002493	.0000010
February 7, 2002	38	33.6	.005597	.0000022
March 7, 2002	56	35.8	.005967	.0000024
March 26, 2002	41	7.4	.001240	.0000005
April 11, 2002	63	81.0	.013493	.0000053

Table 1-3. Suspended-sediment data collected at the 26th Street Bridge, Allegan streamgage.

Sampling date	Discharge (cubic meter/ second)	Concen-tration (milligram/ liter)	Transport rate (cubic meter/ second)	Sampling date	Discharge (cubic meter/ second)	Concen-tration (milligram/ liter)	Transport rate (cubic meter/ second)
February 13, 2001	113	81	0.003445	June 12, 2001	69	67	0.001733
February 26, 2001	110	21	.000873	June 12, 2001	69	67	.001747
February 27, 2001	105	20	.000791	June 22, 2001	57	76	.001641
March 1, 2001	115	17	.000739	July 2, 2001	36	50	.000679
March 2, 2001	113	15	.000641	July 16, 2001	24	33	.000303
March 4, 2001	97	32	.001170	July 18, 2001	33	30	.000372
March 7, 2001	77	13	.000379	July 22, 2001	46	63	.001084
March 7, 2001	77	10	.000292	July 25, 2001	37	34	.000469
March 11, 2001	67	52	.001317	August 9, 2001	30	17	.000193
March 17, 2001	69	36	.000935	August 17, 2001	34	26	.000333
March 20, 2001	62	19	.000443	August 23, 2001	86	47	.001517
March 24, 2001	57	45	.000967	September 3, 2001	35	47	.000613
March 28, 2001	50	45	.000846	September 11, 2001	44	29	.000480
April 5, 2001	49	28	.000521	September 18, 2001	34	39	.000500
April 11, 2001	58	47	.001025	September 22, 2001	58	24	.000526
April 17, 2001	48	42	.000754	September 28, 2001	47	33	.000589
April 23, 2001	75	136	.003866	October 5, 2001	54	47	.000959
April 27, 2001	69	90	.002337	October 15, 2001	100	37	.001396
May 2, 2001	50	29	.000552	October 25, 2001	111	45	.001885
May 6, 2001	43	50	.000807	October 31, 2001	74	27	.000759
May 13, 2001	43	43	.000694	November 3, 2001	76	38	.001092
May 15, 2001	74	71	.001988	November 13, 2001	54	36	.000731
May 16, 2001	97	244	.008970	November 19, 2001	51	47	.000899
May 16, 2001	105	202	.008009	November 27, 2001	53	52	.001045
May 17, 2001	95	29	.001038	November 30, 2001	63	41	.000981
May 22, 2001	94	38	.001352	November 30, 2001	66	39	.000967
May 22, 2001	126	39	.001855	December 14, 2001	51	40	.000765
May 22, 2001	126	37	.001760	December 17, 2001	64	46	.001111
June 1, 2001	82	29	.000893	December 26, 2001	57	38	.000812
June 6, 2001	76	41	.001170				

Appendix 2. Simulated streamflow data for the 1947 flood at the Plainwell streamgage, Plainwell, Michigan

Table 2-1. Simulated daily mean streamflows generated from the daily mean streamflow data at the Comstock streamgage. These values were used in creating the 1947 flood scenario in the study reach.

Number of days	Discharge (cubic meter/ second)	Temperature (degree celcius)	Number of days	Discharge (cubic meter/ second)	Temperature (degree celcius)	Number of days	Discharge (cubic meter/ second)	Temperature (degree celcius)
1	61.4	9.4	21	93.0	9.4	41	63.4	12.5
2	60.4	9.4	22	86.0	9.4	42	75.1	12.5
3	60.3	9.4	23	72.2	9.4	43	77.2	12.5
4	60.4	9.4	24	66.5	9.4	44	59.9	12.5
5	58.9	9.4	25	62.9	9.4	45	59.4	12.5
6	56.6	9.4	26	61.3	9.4	46	50.6	12.5
7	53.0	9.4	27	65.9	9.4	47	44.3	12.5
8	46.5	9.4	28	67.9	12.5	48	42.4	12.5
9	46.3	9.4	29	71.9	12.5	49	36.9	12.5
10	56.5	9.4	30	81.7	12.5	50	34.3	12.5
11	64.5	9.4	31	83.1	12.5	51	40.5	13.5
12	99.0	9.4	32	78.9	12.5	52	42.5	13.5
13	157.9	9.4	33	72.7	12.5	53	44.2	13.5
14	184.6	9.4	34	61.3	12.5	54	45.3	13.5
15	235.2	9.4	35	53.8	12.5	55	51.9	13.5
16	224.8	9.4	36	48.3	12.5	56	56.6	13.5
17	199.0	9.4	37	47.7	12.5	57	61.0	13.5
18	163.5	9.4	38	49.1	12.5	58	65.7	13.5
19	134.3	9.4	39	46.8	12.5	59	75.0	13.5
20	104.7	9.4	40	53.0	12.5	60	76.8	13.5

Appendix 3. Computed values of Manning's roughness coefficient for the alluvial section of the Kalamazoo River, Michigan

Table 3-1. Computed values of Manning's roughness coefficient.

Transect number	Manning's *n* values	Transect number	Manning's *n* values	Transect number	Manning's *n* values	Transect number	Manning's *n* values	Transect number	Manning's *n* values
Transect 1	0.02	Transect 28	0.02	Transect 54	0.02	Transect 80	0.05	Transect 106	0.02
Transect 2	.02	Transect 29	.02	Transect 55	.02	Transect 81	.05	Transect 107	.02
Transect 3	.02	Transect 30	.02	Transect 56	.02	Transect 82	.04	Transect 108	.02
Transect 4	.04	Transect 31	.02	Transect 57	.02	Transect 83	.04	Transect 109	.02
Transect 5	.04	Transect 32	.02	Transect 58	.02	Transect 84	.04	Transect 110	.02
Transect 6	.04	Transect 33	.02	Transect 59	.02	Transect 85	.02	Transect 111	.02
Transect 7	.05	Transect 34	.02	Transect 60	.02	Transect 86	.02	Transect 112	.02
Transect 8	.05	Transect 35	.02	Transect 61	.02	Transect 87	.03	Transect 113	.02
Transect 9	.05	Transect 36	.02	Transect 62	.03	Transect 88	.03	Transect 114	.02
Transect 10	.03	Transect 37	.02	Transect 63	.03	Transect 89	.03	Transect 115	.02
Transect 11	.03	Transect 38	.03	Transect 64	.03	Transect 90	.04	Transect 116	.02
Transect 12	.03	Transect 39	.03	Transect 65	.02	Transect 91	.03	Transect 117	.02
Transect 13	.03	Transect 40	.03	Transect 66	.02	Transect 92	.04	Transect 118	.02
Transect 14	.03	Transect 41	.03	Transect 67	.02	Transect 93	.04	Transect 119	.02
Transect 15	.03	Transect 42	.03	Transect 68	.02	Transect 94	.04	Transect 120	.05
Transect 16	.04	Transect 43	.03	Transect 69	.02	Transect 95	.04	Transect 121	.05
Transect 17	.04	Transect 44	.03	Transect 70	.06	Transect 96	.06	Transect 122	.05
Transect 18	.04	Transect 45	.03	Transect 71	.06	Transect 97	.06	Transect 123	.05
Transect 19	.04	Transect 46	.03	Transect 72	.04	Transect 98	.02	Transect 124	.05
Transect 20	.04	Transect 47	.03	Transect 73	.04	Transect 99	.03	Transect 125	.05
Transect 21	.04	Transect 48	.03	Transect 74	.04	Transect 100	.03	Transect 126	.02
Transect 22	.04	Transect 49	.03	Transect 75	.04	Transect 101	.03	Transect 127	.02
Transect 23	.02	Transect 50	.03	Transect 76	.04	Transect 102	.02	Transect 128	.02
Transect 24	.02	Transect 51	.03	Transect 77	.07	Transect 103	.02	Transect 129	.02
Transect 25	.02	Transect 52	.02	Transect 78	.07	Transect 104	.02	Transect 130	.02
Transect 26	.02	Transect 53	.02	Transect 79	.04	Transect 105	.02	Transect 131	.02
Transect 27	.02								

For additional information write to:
Chief, Michigan District
U.S. Geological Survey
6520 Mercantile Way
Lansing, MI 48911
or visit our Web site at
http://mi.water.usgs.gov

USGS

Syed and others—**A Pre-Dam-Removal Assessment of Sediment Transport for Four Dams on the Kalamazoo River between Plainwell and Allegan, Michigan**—SIR 2004-5178

125 years of
science
for America

1879–2004

Printed on recycled paper